COMPUTATIONAL MODELING OF CLIMATE CHANGE, LARGE-SCALE LAND ACQUISITION, AND HOUSEHOLD DYNAMICS IN SOUTHERN ETHIOPIA

by

Atesmachew Bizuwerk Hailegiorgis
A Dissertation Submitted to the
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In Partial fulfillment of
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of
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Computational Social Science

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Fairfax,VA

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DEDICATION

This dissertation is dedicated to my mother Desta Adank and to my late father Bizuwerk Hailegiorgis.

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LIST OF ABBREVIATIONS

ABM	Agent-Based Models/Modeling
AN	Above Normal rainfall
BN	Below Normal rainfall
CAS	Complex Adaptive Systems
CRU-TS	Climatic Research Unit - Time Series
CSA	Central Statistics Agency of Ethiopia
CSV	Comma Separated Value
DEM	Digital Elevation Model
DM	Dry Matter
EC	Early Cessation
EO	Early Onset
FAO	United Nations Food and Agriculture Organization
GIS	Geographic Information Systems
GUI	Graphic User Interface
HA	Hectare
IFPRI	International Food Policy Research Institute
IPCC	Intergovernmental Panel on Climate Change
KM	Kilometer
LC	Late Cessation
LGP	Length of Growing Period
LO	Late Onset
MASON	Multi-Agent Simulator Of Neighborhoods /Networks
MEQ	Maize Equivalent
MER	Minimum Effective Rain
M.A.S.L	Meters above sea level
MODIS	Moderate-resolution Imaging Spectroradiometer
MoFED	Ministry of Finance and Economic Development of Ethiopia
MPPACC	Model of Private Proactive Adaptation to Climate Change
NA	Normal Amount rainfall
NC	Normal Cessation
NDVI	Normalized Difference Vegetation Index
NO	Normal Onset
NSF	National Science Foundation
ODD	Overview, Design concepts, Details

SEZs	Special Economic Zones
SNNPR	Southern Nations, Nationalities, and People's Region of Ethiopia
SQ	Squrare
SRTM	Shuttle Radar Topography Mission
TLU	Tropical Livestock Units
UML	Unified Modeling Language
UNECA	United Nations Economic Commission for Africa
UNEP	United Nations Environment Programme
WFP	United Nations World Food Programme

ABSTRACT

COMPUTATIONAL MODELING OF CLIMATE CHANGE, LARGE-SCALE LAND ACQUISITION, AND HOUSEHOLD DYNAMICS IN SOUTHERN ETHIOPIA

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Goerge Mason University, 2013

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This dissertation investigates, models, and tests hypotheses on how the current surge in large-scale land acquisition might affect rural livelihood in developing countries. The focus is on southern Ethiopia, specifically the South Omo zone, where ongoing large-scale land acquisition transactions, climate-stressed rural communities, and biodiversity provide a valuable research opportunity to better understand these complex dynamics. The study presents a computational model, OMOLAND, which is a spatial agent-based model that explicitly represents the main components of the rural system (households, enterprises, institutions, climate, and biophysical environment), their interactions, and dynamics. The main findings are:

- Although the rural communities in the South Omo zone manage to persist with the current climate condition, the occurrence of successive episodes of extreme events

(drought) affects their adaptive capacity and forces them to migrate out of the system in greater magnitude.

- Although, the introduction of commercial enterprises in rural system minimize rural households' vulnerability to climate variability through opening up off-farm opportunity, increasing the magnitude of expansion of large-scale land acquisition aggravate dispossession and increase migration of rural households as the system transit to new phases.
- The intervention of institution through capacity building and relief support in the time of extreme events minimizes the number of people migrating from the system.

The study contributes to broaden current scientific understanding of complex coupled human and natural systems through explicitly modeling the dynamics of heterogeneous actors, institutions, and their environments. The modeling approach complements current efforts aimed at integrating GIS and agent-based models for basic research and policy analysis, providing an innovative and significant methodological thrust in computational social science and geospatial modeling.

1 INTRODUCTION

1.1 Motivation

How are local human communities and ecosystems affected by large-scale land acquisition in developing countries currently stressed by climate change? This dissertation investigates, models, and tests hypotheses on how the current surge in large-scale land acquisition (a.k.a. "land-grabbing") might affect rural livelihood in developing countries; how such new policy interventions affect ecosystems including local traditional societies. The focus is on southern Ethiopia; particularly on the South Omo zone[1], where ongoing large-scale land acquisition transactions, climate-stressed rural communities, and biodiversity provide a valuable research opportunity to better understand these complex dynamics.

The systems in which rural communities reside have continually been affected by changes in the socioeconomic environment, political instability, and climate variability. Climate uncertainty and seasonal variability directly affect their livelihood as the majority of them rely upon a rain-dependent agriculture system.

Recently, the surge in large-scale land acquisitions is becoming a major concern alter-

[1] Zone is the second-level administrative divisions of Ethiopia after Region, which is the first-level administrative divisions of Ethiopia. Woreda is the third-level administrative divisions of Ethiopia.

ing the dynamics of the rural systems and affecting the adaptive capacity of rural communities. Although most of the rural communities have developed different kinds of adaptation mechanisms to prolong their livelihood, the introduction of agri-business enterprises (both national and international origins) and the subsequent rapid change in landuse systems are challenging the traditional way of life.

The resilience of such a system under future climate and socioeconomic uncertainty, and the complexity of the dynamics (i.e., heterogeneous actors/agents, nonlinear interactions, emergent micro-macro dynamics, and multiple spatiotemporal scales) pose a significant scientific challenge. Investigating the interaction of enterprises and rural communities, as well as the influence of commercialization of land on rural livelihoods and ecosystem, is key to improving policies for enhancing the wellbeing of rural communities and maintaining the sustainability of ecosystem functions and processes.

1.2 Overview of Current Large-scale Land Acquisition

The current surge in large-scale land acquisition in many developing countries has become a global (or at least a transnational) issue, attracting attention due to the scale and speed of acquisition [155]. This now occurs in many developing countries around the world, especially in Sub-Saharan Africa—the area of the world with the highest hunger indices [156]—on a scale where a single enterprise could acquire nearly 500,000 hectares of land in a single purchase [46]. These land acquisitions also involve diverse interest groups, both national and international. Moreover, the sources of investments are diverse, including privately owned, government-backed, and sovereign wealth fund investments.

Multiple lines of evidence yield the same overall trend in large-scale land acquisition in developing countries generally, and Sub-Saharan Africa in particular, including Ethiopia. The International Food Policy Research Institute (IFPRI) estimated that nearly 20 million hectares of farmlands in developing countries have been acquired by enterprises since 2006 [156]. A World Bank study conducted in the same years, based on broader data sources including media reports, raised the figure to 57 million hectares [46]. Of these, more than two-thirds were in Sub-Saharan Africa [46]. Another empirical study by Cotula et al. [36] also showed that between 2004 and 2008 a total of 2.5 million hectares of land was acquired by national and international enterprises in five African countries: Ghana, Madagascar, Mali, Sudan, and Ethiopia. A recent study by The Oakland Institute, an independent policy think-tank, reports that in Ethiopia alone the total amount of lands leased to foreign and national enterprises increased from about 1.2 million hectares between 2004 and 2008 to nearly 3.6 million hectares as of January 2011 [121].

Multiple processes drive the current phenomenon of large-scale land acquisition, the most common being demand for food and biofuel production. The empirical study by Cotula et al. [36] in five African countries (Ethiopia, Ghana, Madagascar, Mali, and Sudan) indicated that, out of the total 2.5 million hectares that were leased out to different domestic and foreign enterprises between 2004 and 2008, nearly 1.4 million hectares were for food and 1.1 million for biofuel production. Zoomers [160] argues that there are additional, competing, and equally important drivers of large-scale land acquisition, managed by transnational investment groups capable of significantly changing land ownership and the traditional landuse system. Recently increased involvement by private enterprises and international organizations in the development of protected areas, nature reserves, ecotourism businesses, and construction of large-scale tourist complexes promote the conversion of productive lands into attractive tourist destinations. Demand for achieving economic growth also promotes the creation of Special Economic Zones (SEZs) [160]. National elites and urban middle classes are also increasingly engaged in small-scale to large-scale land acquisition for a variety of investments, including food and biofuel production. Cotula et al. [36] revealed that out of the 2.5 million hectares of land in the five countries already mentioned (including Ethiopia), land acquisition by national enterprises accounts for 0.394 million hectares, approximately 16%; almost a third of total acquisitions.

In Ethiopia, increases in income inequality between rural and urban communities [46] and drought frequency have recently prompted the government of Ethiopia to implement policies that might reduce such inequalities while also boosting agricultural production through technological improvements. One of the main ways in which the government intends to develop the agricultural sector is by "commodification" of the land, whereby a rural society of many small farmers and subsistence agriculture is transformed into capital-intensive production enterprises to feed a growing urban population [117]. There is great interest in understanding the implications of such large-scale land acquisition especially in relation with rural systems.

1.3 Overview of the Study Area

The South Omo zone of Ethiopia is rich in resources (fertile soils, rivers, irrigable lands) and has great potential for various agriculture production systems (both livestock and crop production). The local population consists of indigenous tribes living in a traditional system of subsistence agriculture. Recently, the zone has come into public spotlight due to the growing trend on large-scale land acquisition. This trend in land acquisitions will likely bring major changes to the currently stable rural system. Growing pressures from national and international enterprises favoring large-scale agricultural production and ecotourism, and shifts in government policies induce changes in eco-social dynamics, potentially affecting the adaptive capacity of rural households by limiting access to traditional resources.

1.4 Research Goals

The goal of this dissertation is twofold. First, it aspires to explore the impact of climate change and large-scale land acquisition on rural communities and their livelihood decisions, and the ultimate impacts of such decisions on the regional ecology viewed as a complex adaptive system with coupled natural and human systems. Second it aims to develop a computational model that explicitly represents major actors (enterprises, households, and institutions), climate, and the biophysical environment. It uses the simulation model to conduct computational experiments to investigate and better understand the effects of large-scale land acquisitions (positive/negative) on the adaptive capacity of rural households under different climate scenarios.

1.5 Research Questions

The central question in this dissertation asks: *how are local human communities and ecosystems affected by large-scale land acquisition in developing countries currently stressed by climate change?* In particular, this dissertation attempts to answer the following research questions:

- how can rural households sustain their livelihood under different climate variations? Is the current adaptive mechanism of rural households resilient to future climatic shocks?

- how are rural households affected by large-scale land acquisition? Will this change in the status quo lead to dispossession or displacement?
- what will be the combined effects of climate change and expansion of large-scale land acquisition on households? Can the presence of enterprises in the system enhance household livelihood consistent with development aspirations?
- can institutional support to increase the adaptive capacity of rural households minimize the impact of climate variability and large-scale land acquisition on rural communities?

1.6 Overview of the Research Topic and Methodology

The research topic of this dissertation focuses on investigating social consequences of large-scale land acquisitions in the South Omo zone, given a range of scenarios in regional climate change, economic, and policy changes. The study addresses the issue by relies on existing theories and methods mainly in the field of complex systems, GIS, landuse and land cover change, and climate change adaptation.

This dissertation approaches the problem by considering the South Omo zone as a complex coupled human and natural systems, comprising a set of interrelated components interacting at different spatial and temporal scale. The main conceptual components are: rural households, enterprises, government institutions and their policies, and the biophysical environment including climate.

This dissertation presents a computational model, OMOLAND, which represents major actors (enterprises, households and institutions) and their interactions among themselves and with the environment in southern Ethiopia. Besides its strong GIS (Geographic Information Systems) integration for representing spatial features, the OMOLAND model explicitly represents the socio-cognitive processes of rural households used in climate change adaptation. The underlying principles of household adaptive behavior are constructed based on a Model of Private Proactive Adaptation to Climate Change (MPPACC) by Grothmann and Patt [77].

The following are novel methodological features and research contributions of the OMOLAND model:

- It explicitly represents and captures the interaction of the main components of the rural systems.
- It captures the proactive adaptive behavior of rural households.
- It models the climate variability using multi-temporal real rainfall data.
- It is a spatially explicit models, which extensively utilizes GIS, both as model input data, and for model visualization.
- It represents the main entities at higher temporal and spatial resolutions.

- It has a facility to capture different spatial and statitcical model outputs of the model runs.

- It has a strong model visualization facility, which not only shows the interaction and dynamics of major components of the model but also provides different statistical output to monitor the dynamics of the model at runtime.

1.7 Preview of Chapters

This dissertation is structured in five main chapters.

The first chapter provides detailed information on what motivates this dissertation study. It gives a detail account of the current challenge of rural households in most developing countries. It states the main purpose of this dissertation study and the types of research questions that this dissertation will address through computational social science theories and methods.

Chapter two focuses on exploring the current understanding of rural systems. It starts by describing the characteristics and current challenges of the study area. Then it provides a review of literature that focuses on how the main challenges of the study area fit with the current theories on rural systems, and how those challenges are addressed through computational methods. Finally it highlights the gaps in current modeling approaches.

The third chapter is dedicated to the modeling concepts and implementation. It presents the research procedure implemented in developing the model. Then, the main themes that the model is intended to address are presented. Before presenting the model implementation, it provides the conceptual representation of the OMOLAND model, which results from the current theories and understanding of the rural systems in the context of the study area. Then a detailed description of the model implementation is presented. Finally, it describes the effort made to verify and validate the model.

Chapter four presents the three main computational results that address the three research themes. It also discusses each of the research results. The first section is dedicated to results and discussion on the impact of climate change on rural households. The second section presents results and discussion on enterprise and household interaction under different climatic variability. Finally, the implication of institution on rural systems is presented.

The fifth and final chapter recapitulates the main results and discusses them with respect to the research questions. It also presents the broader scientific and policy implications of this dissertation study. Finally it presents the limitations of the dissertation and outlines potential future research directions.

2 RESEARCH ON RURAL SYSTEMS

2.1 Introduction

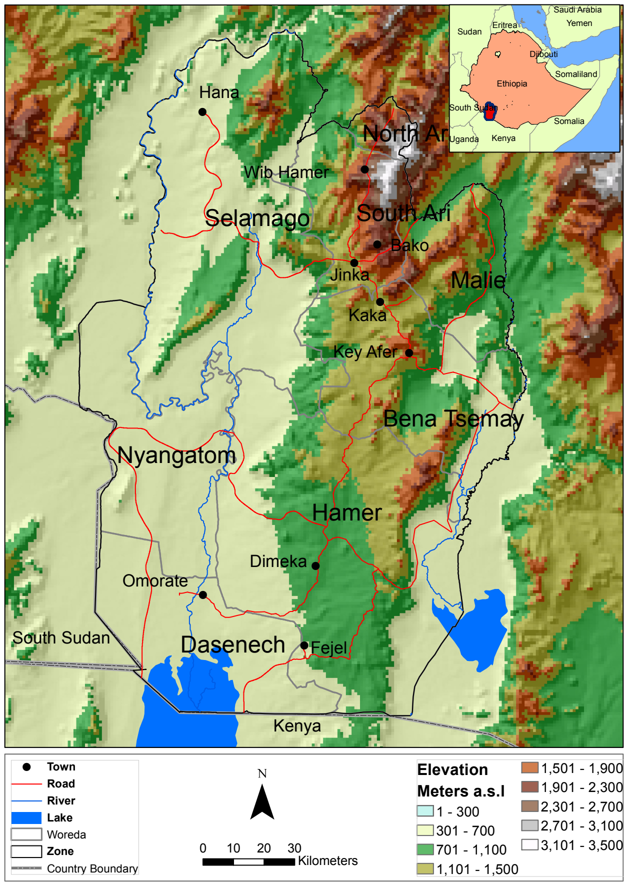
This section highlights the current knowledge of rural systems from the perspective of complex adaptive systems. Complex adaptive systems (CAS) are "systems in which the components, and the structure of interactions between the components, are able to adapt themselves to internal and external disturbances" [85]. A CAS approach also enables analysis of the complexity involved in human decision-making processes at different spatial, organizational, and temporal scales [39, 88, 99].

We first describe the study area by focusing on issues related to climate change adaptation and large-scale land acquisition dynamics, which is relevant for developing the conceptual method and identifying the determinants of rural systems. Next, we present different theories and empirical studies on the two core factors that this dissertation focuses on: implications of climate change on rural systems, and implications of large-scale land acquisition on rural systems. We then discuss prior agent-based modeling efforts particularly related to rural systems. Finally, we present the gaps in current studies on rural systems and agent based modeling in understanding the complex interaction of rural households with climate change and agri-based enterprises in rural systems. Hence, this section lay the foundation for the designing and building of the model that is presented in sections 3.2 to 3.5.

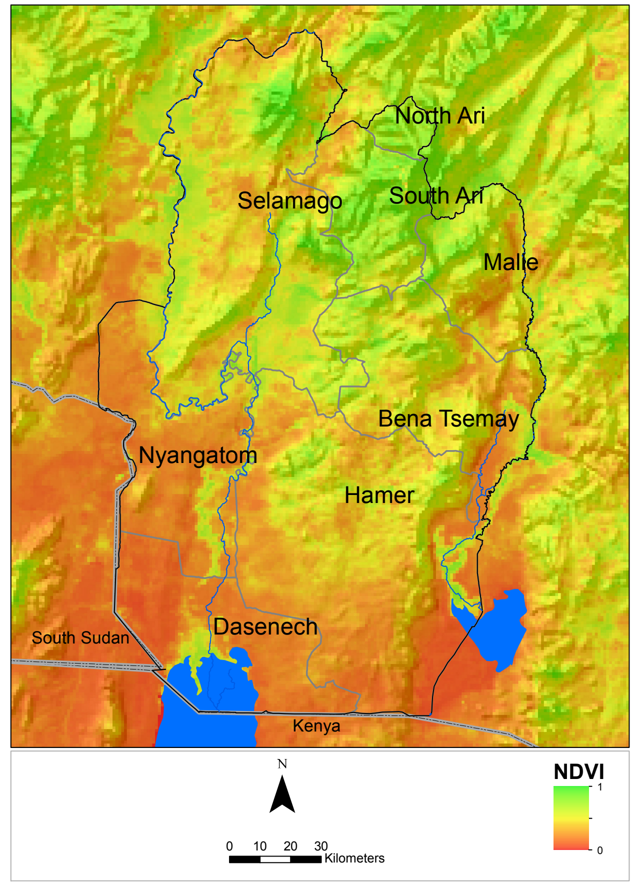
2.2 The South Omo Zone

The South Omo zone, which is one of the zones of the Southern Nations, Nationalities, and People's Region (SNNPR) of Ethiopia, is one of the most important coupled human and natural systems in eastern Africa. It is comprised of arid and semi-arid regions, which are characterized by low and erratic rainfall, periodic droughts, and different types of vegetative cover and soils. It covers an area of 2.3 million hectares located in the southern part of Ethiopia. It borders Kenya in the south and South Sudan in the southwest as shown in Figure 1.

The topography of the zone shows a distinct gradient along a northeast-southwest direction. At the northeast of the zone, the elevation ranges between 2500 – 3500 meters above sea level (m.a.s.l.), while in the southwest the elevation drops significantly and falls between 400 – 500 m.a.s.l as shown in Figure 1a. Along the elevation gradient, the vegetation cover exhibits variation as shown in Figure 1b. The lowlands are covered dominately with grasslands and woodlands while the highlands are covered with shrubs and trees. The zone is intersected by the Omo River running north to south, draining the higher rainfall areas in the northern part of the zone into Lake Turkana. Along the southeast side, it is intersected by the Woito River, which drains the northeast escarpments into the Chew-Bahir (aka “Salt-Sea”).



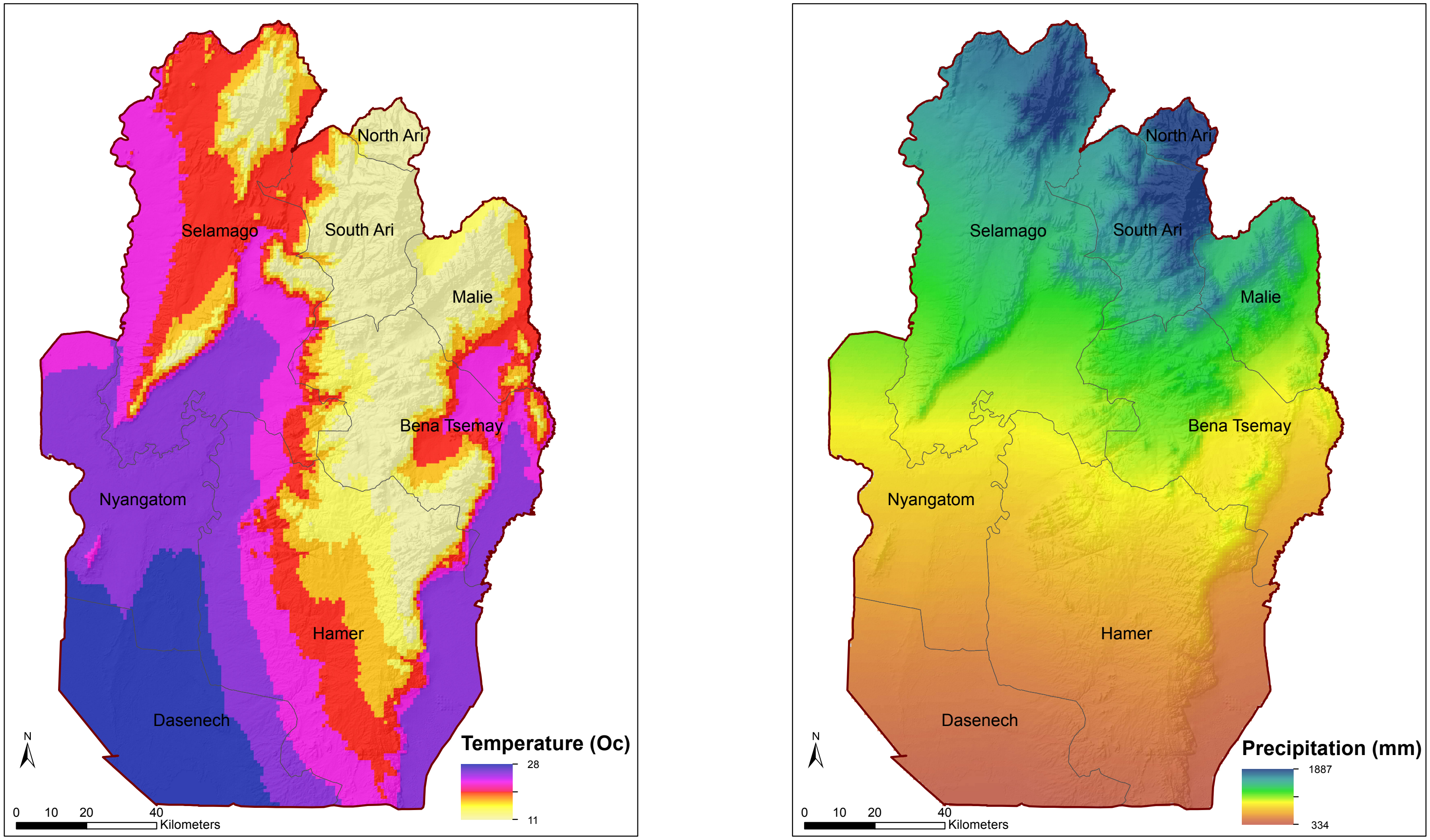
(a) Topography (Data Source: [89])



(b) Normalized Difference Vegetation Index (NDVI) (Data Source: [101])

Figure 1: Geographical location of the South Omo zone of Ethiopia

The climate shows a relatively constant mean annual temperature of 25 °C as shown in Figure 2a. The average maximum daily temperature changes along the elevation gradient from 25 °C on the northeast mountainous area to 33 °C in the southwest. The minimum temperature varies from 20 °C in the hottest month of December – January to 10 °C during June – August. Rain falls mostly in a bimodal pattern across the region, with the long season rain during February – April, and short season rain in September – November. The rain may happen as one long period or may entirely fail to happen. As shown in Figure 2b, the mean annual rainfall patterns shows a strong gradient with less than 400 millimeters (mm) in the southwest and with above 1000 mm in the northeast .



(a) Mean daily temperature (Data Source: [42])

(b) Mean annual precipitation (Data Source: [42])

Figure 2: Climate indices of the South Omo zone

Based on the 2007 Census [41], the total population of the zone is 569,448, of which 284,781 (50.01%) are males and 284,667(49.99%) are females [41]. The total number of households is 125,009 with an average household size of 4.6, of which about 80% are male-headed households while the remaining 20% are female-headed households. Although the zone is less populated (24 people per sq. km) as compared to the population density of the country (82.95 people per sq. km), there is an increasing trend in population growth. As shown in Table 1, the total population in 2007 shows a 75% increase from the total population in 1994 [40].

Table 1: Population of the South Omo zone in 1994 and 2007 by Household size (Source: [40] [41])

Household Size	1994		2007		Percentage Change (1994 -2007)
	Population	Households	Population	Households	
1	7938	7938	12668	12668	60
2	23646	11823	30804	15402	30
3	41094	13698	54129	18043	32
4	52876	13219	78100	19525	48
5	55505	11101	88775	17755	60
6	48618	8103	90834	15139	87
7	36106	5158	73696	10528	104
8	24624	3078	84376	10547	243
9	15165	1685	19764	2196	30
10+	18910	1891	36302	3206	92
Total	324482	77694	569448	125009	75

There is a strong connection between population density, economic activities, topography, and rainfall pattern in the zone. The most densely populated area is found in the highlands where there is sufficient rainfall for agriculture production while the least densely populated area is found in the marginal and lowland area of the zone, which is mainly dominated by the livestock production system as shown in Figure 3 . As indicated in Table 2, South Ari woreda is the most inhabited woreda, accounting for 36.7 % of the total population, followed by Malie (14.9%), while Nyangatom (3.1%) and Selamago (4.9%) are the least inhabited woredas. The zone has a population density of 24.4 people per sq. km. The most densely populated woreda is North Ari (239.6 people per sq. km) while the least densely populated woreda is Selamago (4.8 people per sq. km).

Table 2 shows the livestock distribution by woreda. Nyangatom possesses the highest number of livestock per capita as compared to the remaining woredas while South Ari has the least followed by Malie. In the remaining woredas, the livestock per capita ranges between 2.82 to 4.91 tropical livestock units (TLU) per person. Tropical livestock units is a convenient method for quantifying a wide range of different livestock types and sizes in a standardized manner [83].

Table 2: Population by woreda (Source: [41])

Woreda	Total Area (Sq.km)	Population			%	Density (People/sq.km)	Livestock (TLU/Person)
		Male	Female	Total			
Selamego	1520.7	14,018	13,731	27,749	4.9	4.8	2.88
South Ari	6158.7	102,439	106,550	208,989	36.7	137.4	0.60
North Ari	2548.5	33,333	34,049	67,382	11.8	239.6	3.05
Hamer	5812.4	29,473	29,478	58,951	10.3	9.6	4.91
Bena Tsemay	2925.5	25,662	26,130	51,792	9.1	17.7	3.09
Dasenech	281.2	26,728	25,680	52,408	9.2	20.5	4.24
Malie	2646.4	42,827	41,813	84,640	14.9	59.1	1.24
Nyangatom	1432.2	8,799	8,738	17,537	3.1	6.6	21.10
Total	23325.6	283,279	286,169	569,448	100	24.4	2.83

The infrastructure of the zone is very poor. It has 462 kilometers of all-weather road and 412 kilometers dry weather road, for an average road density of 37 kilometers per 1000 square kilometers, joining the major towns in the zone (e.g. Jinka, Turmi, Omorate). In the rainy season, accessibility becomes even more difficult due to overflow of major rivers, especially the Omo River. Such poor infrastructure diminishes the market linkage of the zone with the major nearby towns and with the neighboring countries. The problem can be easily seen especially if one considers the potential of livestock trade in the zone. There is no major livestock trade outlet as has been seen in other pastoral regions in the country such as the Afar and Somali regions. Most of the livestock trade either occur within the zone or with nearby pastoral groups [4].

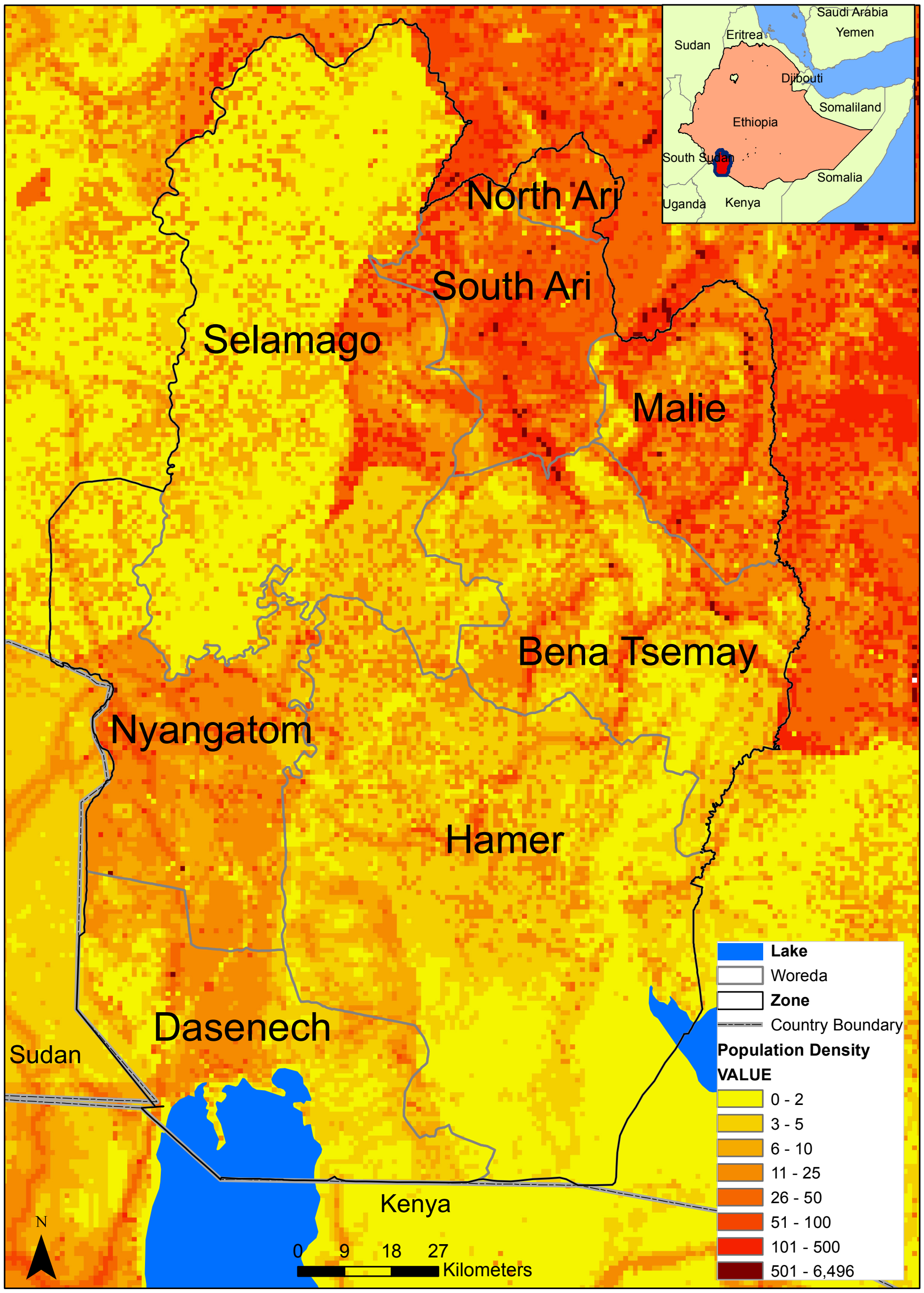


Figure 3: Population density (people per sq. km) of the South Omo zone (Data Source: [127])

2.2.1 Major Economic Activities

The economic activity of the zone is characterized by subsistence agriculture dominated by agro-pastoral and pastoral systems [62, 69]. The crop production system is characterized by a subsistence crop production system mainly targeting the household consumption need. Although there are plenty of opportunities for irrigation and riverine crop production in the zone, the main crop production system is still highly dependent on rain. Among other types of cereals, maize and sorghum account for 90% of the cereal production while wheat and teff are the next main perennial crop. The agricultural cycle follows the two rainy seasons. Planting of staple crops (e.g. maize and sorghum) starts with the onset of the main rainy season (February - June). Staple crops planted in February are harvested in August or September depending of the length of growing period of the crop. The secondary agricultural season commences with the onset of the short rainy season that starts in September and ends in November. Supplementary crops produced in the zone during this period, mainly in the higher altitudes, include: sorghum, wheat, barley, and teff. The average land holding for crop production ranges from 0.1 to 2.0 hectare [41]. The spatial pattern of crop production across the region is mainly dictated by moisture availability [62].

Livestock production occurs mainly in the lowland areas, where moisture is a constraint. In these areas, households realize 80% of their income from the sale of livestock. The main livestock species reared are cattle, goats, and sheep, in that order of importance. Wealth is particularly gauged by cattle ownership: the better off households have up to 70 cattle and up to about 200 small stock (about 70 TLU), while the poor have not more than 5 cattle and 25 small stock (about 6 TLU) [69]. Although livestock raring is the predominant source of livelihood in the lowland areas, some of the communities cover their shortage by engaging in rain-fed crop production. For instance, in the Hamer woreda crop production contributes to upto 20% of the household income. In the mid-altitude where the rainfall amount is greater, the contribution of crop production reaches 50% [62].

Little has been documented in regard to labor employment options in the zone. The most common way of labor activity is labor sharing, which is between relatives, extended families, and neighbors. This sharing is mainly intended to fill a labor gap in order to accomplish a specific task rather than to generate additional income. However, sporadic off-farm activities occur when opportunities arise especially activities related to construction and development work (particularly road construction) in the zone.

2.2.2 Climate Change Adaptation

The climatic condition of the South Omo zone is known for its erratic nature. The rural communities in the zone have managed resources and their livelihood in the face of such challenging climatic condition for many generations. They have applied different coping mechanisms such as increasing herd size, herd diversification, crop diversification and migration in some instances [4, 69]. However the change in climate variation and frequent incidents of extreme climate events affect the biophysical and socioeconomic dynamics of the zone and challenges the adaptive capacity of the communities, as their livelihood is mainly depend on a climate-driven agriculture production system.

2.2.3 Current Large-scale Land Acquisition

The South Omo zone is one of the main land investment areas designated by the country. Currently the federal land administration has assigned about 500,000 hectares of land, which is about 20 % of the total area of the zone, for different investment purposes [121]. The Oakland Institute [121] document indicates that the amount of land currently provided to enterprise reaches to 445,500 hectares. Most of lands are mainly located along the Omo river, which is a major coping mechanism for pastoralists. In drought time, the pastoralists uses the riverbanks both to feed their cattle and to produce crops. For instance, a figure developed by Mousseau and Sosnoff [121] shows that the government demarcates a huge tract of lands for sugar factor along the bank of river Omo as shown in Figure4.

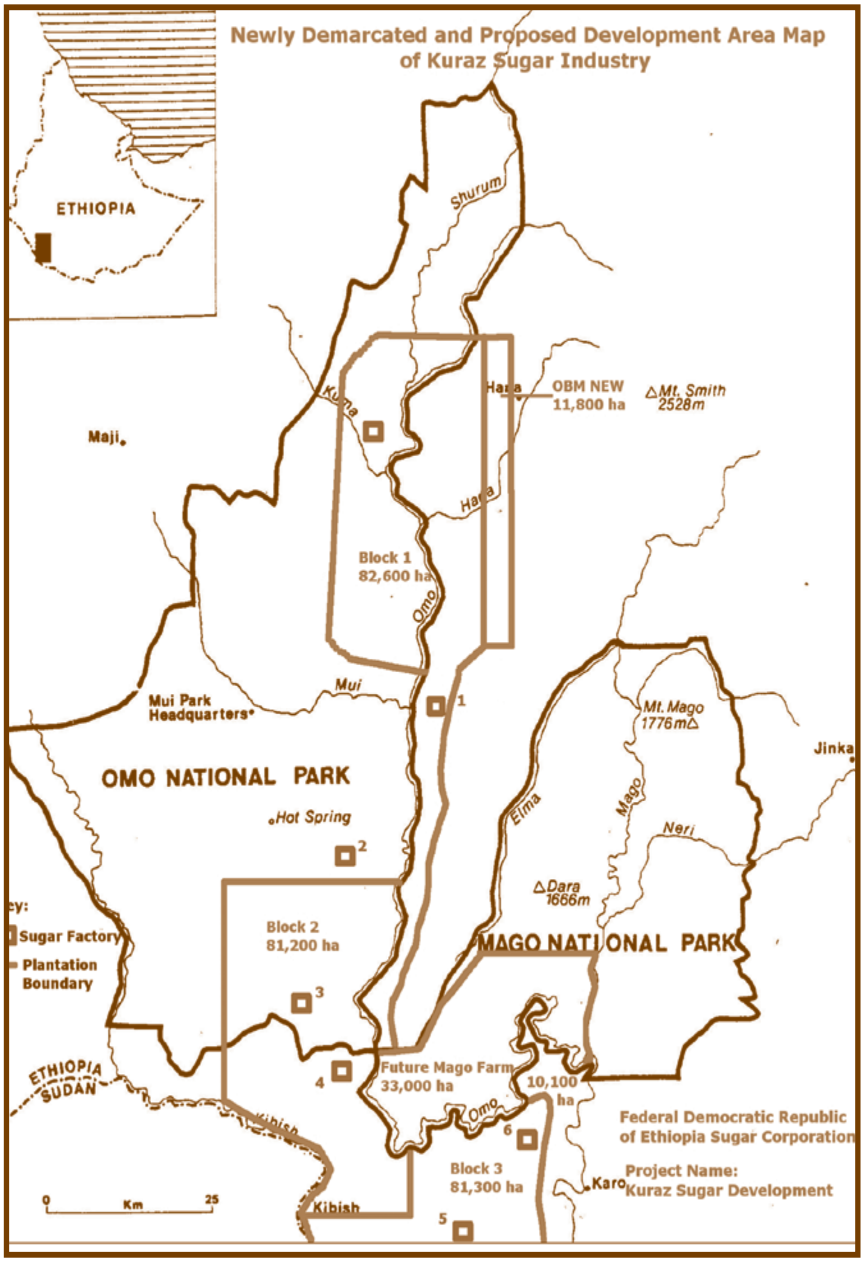


Figure 4: Land allocated to investment near Omo river (Source: [121])

2.3 The Complex Rural System

The rural system in most Sub-Saharan African countries is characterized by interdependent relationships between households that are primarily supported by subsistence agriculture, and the biophysical system with which they are dynamically coupled. Often the rural households are highly dependent on rain-fed agriculture, with climate variability directly affecting agricultural production. Their livelihood decisions are governed by the availability of and opportunity to use resources (social, human, environment, financial). The linkage between the human system and the ecosystem, and the different interactions between these systems at different spatial temporal scales are often considered as complex. Many efforts have been made to unravel the relationship between the human and natural systems and to better understand how these systems interact and affect each other [10, 99, 136].

The rural system developed adaptive strategies over many generations in order to survive in a fragile ecological system: seasonal movement to more productive grazing areas, reciprocal exchange of livestock, formation of social alliances through labor sharing, dowry and marriage, and resolution of conflict through negotiation [53, 128]. It has evolved through different dynamics and transitions, and will likely continue to exist in some form in the future. However, such strategies are gradually disappearing as rapid social, political, and economic changes and difficult climate conditions weaken traditional institutional arrangements [55, 66].

Recurrent drought imposes restrictions on sustainable use of resources, which affects the once highly regarded and accepted customs and adaptive mechanisms. Moreover, the current commercialization of land is so extensive and rapid that it can seriously challenge the system's fundamental adaptive capacity, resulting in unprecedented stress due to a significant alteration of the resource base with insufficient time for adaptation. The speed of change in resource availability places documented limits on adaptive capacity, especially in pastoral and agro-pastoral societies (cf. e.g., Oba [128], Susan [151], Thornton et al. [153]). Displacement and other severe humanitarian consequences may also follow. Such large transformations would generate a significant potential for creating new dynamics that should not be overlooked for their effects on the sustainability of both the traditional rural community and their natural environment.

These changes will likely affect the socioeconomic and biophysical dynamics of the rural system [138], but the complexity of the dynamics poses a significant scientific challenge. Although many studies have been conducted on issues related to rural household dynamics, landuse change, and rural-urban migration (e.g., An [9], Entwisle et al. [57], Rindfuss et al. [141] among others), there are still significant gaps in understanding the impact of large-scale land acquisition on the livelihood of rural households and associated ecosystems. Investigating the interaction of enterprises and rural communities, as well as the influence of commercialization of land on rural livelihoods and ecosystems, is key to improving policies for enhancing the well-being of rural communities and maintaining the sustainability of ecosystem functions and processes. In the next section, we briefly describe the current understanding of climate change trends, their impact on rural system and how rural communities respond to climate variability and climate change in section 2.3.1. We then discuss the current understanding of the impact of enterprise on rural systems in section 2.3.2.

2.3.1 Rural Systems and Climate Change Adaptation

In recent times, climate change and its consequences have received much attention in public and scientific debates. Climate change plays a detrimental role in shaping the socioeconomic system of a society. In societies in which livelihood is highly dependent on agriculture, the impact of climate change is immense. In the next section we briefly discuss the current understanding of climate phenomena and then will provides the impact of climate change on rural systems as well as how rural systems respond to climate variability.

According to the Intergovernmental Panel on Climate Change (IPCC) report [137], there is general agreement on the trend of annual land-surface air temperature has increased over the last 100 years. Hulme et al. [86] described the current temperature in Africa as warmer than it was prior to 100 years ago. They mention that the rate of warming is about 0.5 °C per century. The temperature will continue to increase above the global average mean in all season with more warning in sub tropics than the tropics [137]. Similarly, Paeth et al. [133], who include the current trend of land cover change in Africa in their model, point out that Africa may warm more than 3 °C in the next 50 years. Along with this, extreme temperature and heat waves are also likely to increase by up to 2.5 °C.

Several studies also indicate that there have been noticeable changes in rainfall amount in Africa although the magnitude of change differs from region to region. According to Hulme et al. [86], up to 25 % per century drying is observed in most parts of the Sahel and moderate drying of 5 to 15 % per century observed in southern Africa, while in most parts of East Africa relatively modest wetting of up to 10 % per century is observed. The IPCC report indicates that rainfall will likely continue with the same spatial trend with decrease in most of the region except in Eastern Africa and Sahel. There is likely to be an increase in annual mean rainfall in East Africa while the situation in Sahel remains uncertain[137]. However, recent research suggests that local circulation effects will result in decreased precipitation in Eastern Africa [65]. Extreme change in frequency and intensity of precipitation accompanied with climate extreme events such as flood and drought occur more frequently and with greater variance in Eastern Africa [52, 73, 137].

These anticipated climate changes will likely cause substantial economic and environmental changes in many countries, particularly in Sub-Saharan Africa countries, including Ethiopia, where the economy is highly coupled with climate based agriculture system [104, 112, 114, 137]. The risk from climate change is manifested across space, time, asset classes, and households [5].

Jones and Thornton [90] studied the overall impact of climate change on smallholder agriculture production and smallholder rain-fed systems in Africa and Latin America and suggested that maize yield will likely decrease by about 10% by 2055 in these regions as a result of temperature increases and rainfall variability becoming less conducive to maize production. Winters et al. [157] also provides a gloomy picture of the impact of climate change on developing countries. They indicate that developing countries in Africa, Asia, and Latin America will potentially suffer income and production losses because of climate change.

Morton [119] also suggested that especially smallholder and subsistence farmers in dry tropics are profoundly affected by temperature-induced decline in crop yield, and increasing frequency and severity of drought. Consequently, these changes lead to "increased likelihood of crop failure; increased diseases and mortality of livestock and/or forced sales of livestock at disadvantageous prices; livelihood impacts including sale of other assets, indebtedness, out-migration and dependency on food relief; possible feedbacks through unsustainable adaptation strategies into environmental degradation including loss of biodiversity; and eventual impacts on human development indicators such as health and education" [119]. Given that a climate-driven subsistence agriculture system is the main source of livelihood for most rural communities, adaptation to the adverse effects of climate change is essential to sustain rural livelihoods and to ensure food security [27, 49]. In the context of climate change, adaptation includes all adjustments in behavior or economics that reduce the vulnerability of society to change in the climate system [148]. Hence, such adjustments can greatly reduce vulnerability to climate change by making rural communities proactive to climate change and variability, moderating potential damages, and helping them cope with adverse consequences [112, 137].

Although adaptation to climate change plays a significant role in rural systems, modeling adaptation is a complex, multidimensional, and multi-scale process [27]. In addition, the mechanism in which rural communities respond to climate variability and change is extensively location and context specific. The heterogeneity of rural household characteristics and compositions, the diversity of agricultural and nonagricultural livelihood strategies, and the rate of exposure to various stressors, ranging from natural stressor to those related to socioeconomic and political changes, makes adaptation difficult to model and predict for smallholder and subsistence agriculture [119].

Morton [119] discussed the need to develop a comprehensive approach to understanding the complexity of climate adaptation in subsistence farmers and smallholder communities. Any framework that deals with the impact of climate change on smallholder and subsistence agriculture system should recognize the complexity and location-specificity of rural production systems, should incorporate non-climate stressors on rural livelihoods and their contribution to vulnerability, and focus on the direct impact of climate change on smallholder livelihoods, mainly biological processes at organism and field levels, environmental and physical processes at different spatial scales, and non-agriculture impacts of climate change [119] .

Given the complexity and location-specificity of climate change adaptation, many suggestions and typologies are proposed for adaptation progresses in smallholder and subsistence agriculture systems. Several adaptive measures have been discussed in previous studies including diversifying crops and varieties, changing planting dates, crop rotation, intensification and use of irrigation, expansion of farm lands, implementing different soil conservation mechanisms, diversifying household income sources [34, 49, 114, 132]. Indeed, Kniveton et al. [94] suggested that seasonal migration is also used as an adaptive mechanism in Burkina Faso. Bantilan and Anupama [17] also indicated that rural farmers in India manage to withstand the effect of prolonged drought and climate variability though increased off-farm activity, caste occupations and seasonal migration.

In the context of agro-pastoral rural communities, Agrawal and Perrin [5] suggested that the basic adaptation strategies involve functions that share risks through mobility, storage, diversification, common pooling and exchange of resources. Similar observation is also made by Morton et al. [120] after reviewing several studies on coping strategies of pastoralists during recent drought and long-term adaptations in Northern Kenya and Southern Ethiopia. Morton et al. underlines that the most common adaptation strategies by pastoralists are mobility, increasing herd size, diversifying herd composition, diversifying livelihood, sharing of resources. Thornton et al. [153] also suggested that engaging in farming, herd diversification, and increasing off-farm activities are the most common adaptation in pastoralist settings. Adger et al. [2] observe, in addition, the use of local-based knowledge of resource systems and social network to share risks. Additionally, using open-access resources such as wild foods is also mentioned as a core adaptive mechanism in most pastoral communities [59, 118].

2.3.2 Rural Systems and Agricultural Enterprises

The expansion of large-scale land acquisition can have various influences on the rural system. Earlier studies have linked the activity of such enterprises to the transformation of socioeconomic dynamics in rural systems (e.g., Booth et al. [25], Deininger et al. [46], Derbyshire and Vickers [48], Ellis and Biggs [54], Von Braun et al. [156]), showing that enterprises may contribute to the rural economy by creating jobs, transferring technologies, and developing infrastructure. In many cases, large-scale land acquisitions are oriented toward labor-intensive agriculture creating opportunities for a wage labor market in rural societies [46]. Wage labor enhances household incomes and diversifies livelihood options. It may also help households minimize dependency on subsistence farming, reduce vulnerability to climate change, and increase economic benefits [18]. Moreover, income growth can lead to a self-sufficient lifestyle and limit rural migration to urban centers [44].

The engagement of more capital-endowed enterprises in a rural system can also increase rural infrastructure (e.g., roads, irrigation canals, bridges) as enterprises seek to facilitate their business for maximum economic return. Developments of more infrastructure might expose rural communities to broader opportunities, for instance, linking them to markets and urban areas, minimizing their cost of travel, enhancing agricultural productivity, and improving the prospect for greater public services [28, 47, 60, 100, 142]. Enterprises might also contribute to the rural system by increasing the production performance of land through the introduction of modern technology.

Although households might be better off because of the contributions of enterprises in rural systems, others argue that the current surge of large-scale land acquisition exposes rural households to risks that can affect their livelihood [22, 155]. Expansion of large-scale agricultural systems can deny the customary right of rural households to utilize communal properties, affecting adaptive capacity and increasing vulnerability of households [126]. Considerable expansion of large-scale land acquisition can also lead to dispossession and displacement of local people as most of the lands are already occupied or used by rural households [7]. The premise of changing the rural system to a more capital-intensive agriculture system might neglect the social context of land, which is more than a production entity in most rural societies. Since rural communities consider land as a reflection of identity, appropriation of land by enterprises can cause displacement, loss of socio-cultural fabric (and social capital), increase in grievances and, in some instances, the onset of conflict [56, 66, 72].

The expansion of large-scale land acquisition will also change the rural structure from many smallholding rural households to a few large-holding enterprises. Such structural change in the size distribution of landuse will affect rural households' access to land resources and weaken their social cooperation, because of increased inequality among rural households [29]. Although enterprises might create employment for the rural system, their capacity is still limited and cannot accommodate all rural inhabitants. As more lands are taken by enterprises, and as more households are becoming unproductive, the mismatch between the number of jobs that can be created by the enterprises and the number of rural households can increase to a threshold beyond which displacements occur [18].

The environment is also stressed as more land is converted to agriculture [70]. The conversion of marginal land that is currently either covered by forest or used for grazing will accelerate land degradation and loss of biodiversity [113]. Even if large-scale farming is implemented in existing agricultural lands, the change from multi-cropping to mono-cropping will inevitably make the system more susceptible to drought and disease. Besides degradation and biodiversity loss, increased utilization of chemicals without proper treatment of effluent waters can inflict environmental damage and put human health at risk.

2.4 Prior Agent-Based Modeling Approaches to Rural Systems

Many traditional techniques, such as statistical, equation-based, and system models have been used to study the complexity of rural systems in different contexts [136]. However, these techniques have been highly criticized by their inefficiency at capturing the complex interaction of human and biophysical systems. Such modeling approaches are either over-simplify the representation of the human actor or lack the capacity to capture temporal complexity, spatial complexity, and feedbacks [136]. Hence, to make progress and to gain a greater understanding of the complex interaction of the human and biophysical system, appropriate modeling tools need to be applied.

More recently, understanding the rural system as a complex adaptive system has been given more attention as it provides a greater insight about the rural system by capturing the complex interaction and dynamic feedback between the systems. The application of dynamic modeling could provide additional insights in exploring the impact of climate change and large-scale land acquisition. Angus et al. [11] have suggested that to understand complex, dynamic, and nonlinear challenges faced by climate change, the application of integrated models—such as agent-based models that capture the interaction between individuals and their surrounding environment—is essential. The current understanding of the interaction between humans and their environment as a CAS provides valuable insights on cross-scale properties and dynamics, supported by computational simulation models.

One of the most common ways of studying a CAS is through agent-based modeling (ABM) [58, 88, 116], because agent-based modeling provides a viable scientific approach for representing complex interactions among humans and their environments (both natural and artificial), as well as feedback between them [106, 108, 135, 136]. It is also possible to use agent-based modeling as computational laboratories for exploring interesting scenarios that focus on the local people's adaptive responses to different socioeconomic factors and the underlying effects on their ecosystem [30, 31, 39].

Agent-based modeling provides many advantages as compared to the traditional methods. Bonabeau [24] discussed three main advantages of agent based modeling. First, the agent based approach captures emergent phenomena. Second it provides a natural environment for the study of certain systems and third it is flexible. Emergence phenomena occur due to the interaction of individual entities at micro level. Emergence phenomena are "the macroscopic regularity from the bottom-up" [58]. Emergence is displayed by the resulting macroscopic pattern. This high order regularity occurs without the need for central control. Agent-based modeling also provides a natural way of representing the system under consideration. The human actors and the biophysical system can be easily represents in an agent-based model. Agent-based modeling provides a mechanism to represent heterogeneous agents and their dynamic interaction with each other and the environment. This kind of individual based interaction at local level will determine the behavior of the whole system. This will allow the influence of human decision-making on the environment to be incorporated in dynamic and spatially explicit way. The interaction of agents can be directly with each other through the socioeconomic system such as market, institution and social network or indirectly through the shared environment [87, 108].

Another advantage of ABM is its flexibility to include more agent, behaviors, and other factors that can be relevant to the specific cases. In environment where household are the main actors that causes landuse changes, it is possible to represent agent as households. In this case heterogeneity can be introduce based on the different characteristics of each households, such as household size, land plot size, income etc. When there are more actors like farmers, herders, commercial business owners, local administrative, etc, it is possible to represent each as an agent and provide extra heterogeneity among each agent groups [24]. Because behavior is represented explicitly in ABM, it is easier to communicate with stockholders than other mathematical or statistical models [123]. Despite many advantages of tool for simulation which enable the representation of coupled human and natural systems, their emergent properties and their process dynamics, agent-based modeling faces challenges particularly to carried out standard model verification and validation procedures [38].

Due to theses potentials and advantages of ABM, several studies have been applied ABM to investigating complex dynamics involving human-environment interactions [9, 108, 135, 154]. Several ABMs have examined the interaction between rural households and their environments in developing countries, including assessing the consequences of household decisions' on landuse and land cover change [45, 97–99, 141, 143]; households' migration behavior [57, 94, 149]; vulnerability to climatic factors [1, 23]; adaptation to climate variability [32], climate risk perception in land marker [64], diversification and adoption of new technologies [20, 91]. These prior models provide many insights on complexity in coupled human and natural systems and the impact of human actions on the environment and vice versa (Further reviews of coupled human and natural systems using agent-based modeling can be found in An [9], Matthews et al. [108], Rindfuss et al. [141])

2.5 Gaps in Current Studies

The expansion of large-scale land acquisition will likely affect the socioeconomic and biophysical dynamics of the rural system [138], but the complexity of the dynamics (i.e., heterogeneous actors/agents, nonlinear interactions, emergent micro-macro dynamics, and multiple spatio-temporal scales) poses a significant scientific challenge. Although many ABM studies have been developed to address the complexity of human-environment systems, none of them seems to pay sufficient attention to the combinatory effect of climate change and actors such as enterprises, and their interaction with local households that shape the dynamics of a rural landscape. Existing models focus mostly on individuals and households and their interaction with biophysical environment and climate change. In a review of the current coupled human and natural system studies, Rindfuss et al. [141] identified several limitations in most of the current landuse modeling literature in terms of agent typology, scale of applications, and representation of feedbacks.

Most landuse land cover models consider a simple agent typology architecture in which the heterogeneity of agents is usually incorporated through variation in the characteristics of the households, not in the character of the actors themselves (e.g., households vs. enterprises)[134]. However, a system where households reside usually involves more than one kind of actors. Many competing actors with diverse objectives and goals interact among each other and with the environment at different spatial and temporal scales. The scale of intervention, type of interaction among those actors, and factors affecting their decisions are usually different. Rindfuss et al. [141] suggested that to understand better how human and natural systems function, it is essential to consider the influence of diverse actors, their distinct characteristics, and the different factors affecting their decision-making [9].

Hence, investigating climate adaptation of rural households, the interaction of enterprises and rural communities, as well as the influence of commercialization of land on rural livelihoods and ecosystems, is key to improving policies for enhancing the well-being of rural communities and maintaining the sustainability of ecosystem functions and processes.

3 METHODOLOGY

3.1 Introduction

Our methodology proceeds from model conceptualization (representative abstraction of the South Omo zone in southern Ethiopia), to implementation (in software/code), testing (verification and validation), and analysis (running alternative scenarios and computational experiments via simulations as discused in chapter 4) [31, 71].

3.2 Overview of the Research Procedure: From Questions to Answers

As discussed in section 1.4, this dissertation focuses on exploring the combinatory impact of climate change and enterprise in the rural systems. The current discourse on the impacts of enterprise in the rural system is rather ambiguous as discussed in section 2.3.2. As shown in Figure 5, enterprise may influence the rural system in different ways. It may influence by increasing vulnerability, causing biophysical degradation or by transforming the socioeconomic situation. However, these impacts can be more pronounced as the environment has already been exposed to different climatic viabilities. To capture such complex issues and dynamics of rural systems, we frame the research problems into three different themes. We also formalize the processes by developing a conceptual model that can represent the complexity and dynamics of rural systems. Finally, we implement the conceptual framework into agent based modeling.

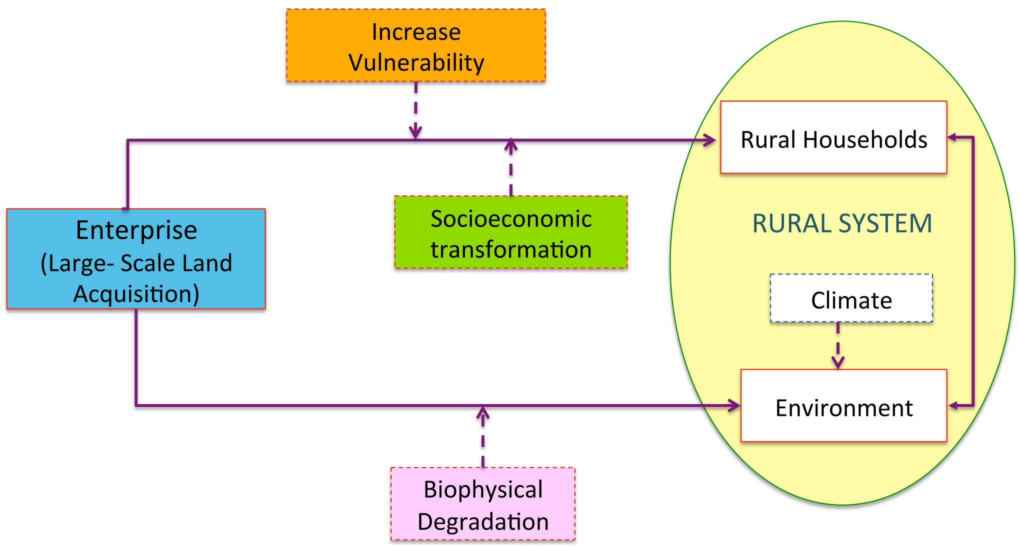


Figure 5: Influence of large-scale land acquisition on rural systems broken lines indicate potential imapcts or indirect relationship between components; bold lines indicate direct relationship between compontents.

3.3 Main Research Themes

The computational analysis activity of this study is organized into three main themes. Each theme addresses a specific topic with associated research questions investigated through computational experiments (simulation runs and scenario analyses).

Theme 1: What are the Impacts of Climate Change on Rural Households?

The main aim of this theme is to gain basic understanding of the resilience and adaptive capacity of rural households with respect to variation in climate, socioeconomic factors, and landuse at the local level. This first model version is used as the "default situation" (status quo ante), to get a baseline for understanding and quantifying the sustainability of rural livelihood for the historical (and until recently) case of households without the presence of enterprises in their ecosystem. Hence, this baseline model will add value by incorporating perception of rural households toward climate change and resource flows that allow agents to diversify their production strategy in their land holdings under different climatic situations and simulation scenarios.

Theme 2: What are the Impacts of Large-scale Land Aquisition on Rural Households?

Theme 2 adds more complexity to Theme 1 through the introduction of enterprise agents. In this theme, we analyze the impact of enterprises on rural households by changing the scale and intensity of intervention of enterprise agents.

First, we explore the impact of enterprises on rural households by limiting their intervention only to unoccupied or marginal lands. Land that is already occupied by any rural household will not be assigned to enterprises unless it is abandoned. This assumption is based on governmental promises of allocating only marginal or unoccupied lands to agri-businesses. Although enterprises might be intervening only on marginal lands, households might be affected as they normally use marginal lands for grazing, seasonal harvesting, or as reserve for future generations [37]. Hence, we explore how household decisions could be influenced by the presence of enterprises in the system. We also assess the contribution of labor wages to household livelihood; i.e., whether households who engage more in labor are better off when climatic variability and economic shocks occur. Besides farming, extra earning from non-farming activities, remittances, and seasonal migrations are considered as subordinate sources of household income, which is highly influenced by households' labor availability, social networks, and biophysical conditions [18]. We quantify the number of households that can successfully live in the system with an increased number of enterprises and climatic variation and measure the social impact of enterprises on households by quantifying the wealth distribution of households (Pareto or log-normal, under normal conditions).

Second, we lift restraints on the allocation of land to enterprises, by extending the biophysical suitability of the land for different commercial investments (including any high-value lands that might be currently owned by local households). In this scenario competition for land between enterprise agents and local households would arguably increase. We test hypotheses about different policy options by increasing/decreasing the intensity and scale of enterprise interventions and measure the magnitude of dispossession of land property and rural household displacement or compliance. In this way we determine where there exist trade-offs between implementation of commoditization of land, persistence of rural livelihood, and sustainability of the ecosystem and, if so, under which conditions.

Theme 3: What are the Impacts of Institutional Interventions on Rural Households?

The third theme, focuses on understanding the influence of institutional intervention in provision of incentive and capacity building to rural households to enhance rural households' adaptation capacity toward climate change. We introduce a very simplified representation of institution agent, which plays on changing the household climate change capacity and also governs the expansion of enterprise agents. This theme addresses issues related to information flow and capacity building to increase the resilience of rural households to economic and climatic changes. We test how much intervention (both capacity building and relief support) can reduce the vulnerability of rural households under climatic and socioeconomic change, particularly changes related to the introduction of enterprises. We test hypotheses about different policy options by increasing/decreasing the learning rate of rural households, the market value of crops and livestock, and at the same time increasing the scale of enterprise interventions.

3.4 Model Conceptualization

We conceptualized the South Omo zone as a complex coupled human and natural system comprising a set of interrelated components interacting at different spatial and temporal scales. System components can be considered as parts of the system that interact in a dynamic way [43]. In the context of coupled human and natural systems, system components include human actors of various kinds (e.g. households, enterprises), particular ecosystem types or habitat types (e.g. farmlands, grasslands, lakes), resources, goods and materials, and abiotic variables as discussed in section 2.3. System components interact or fit together. Examples of relationships are economic and ecological competition, land tenure, and interactions between human actors. To capture the complex interaction and dynamics of the coupled human and natural system in the South Omo, the major components are subdivided into simple units. Figure 6 illustrates the main components, relationships in the model, and the scale of intervention of each system component. The boxes represent the different system components, the bold arrows represent the direct interactions, and the dotted arrows represent the direct interactions between them.

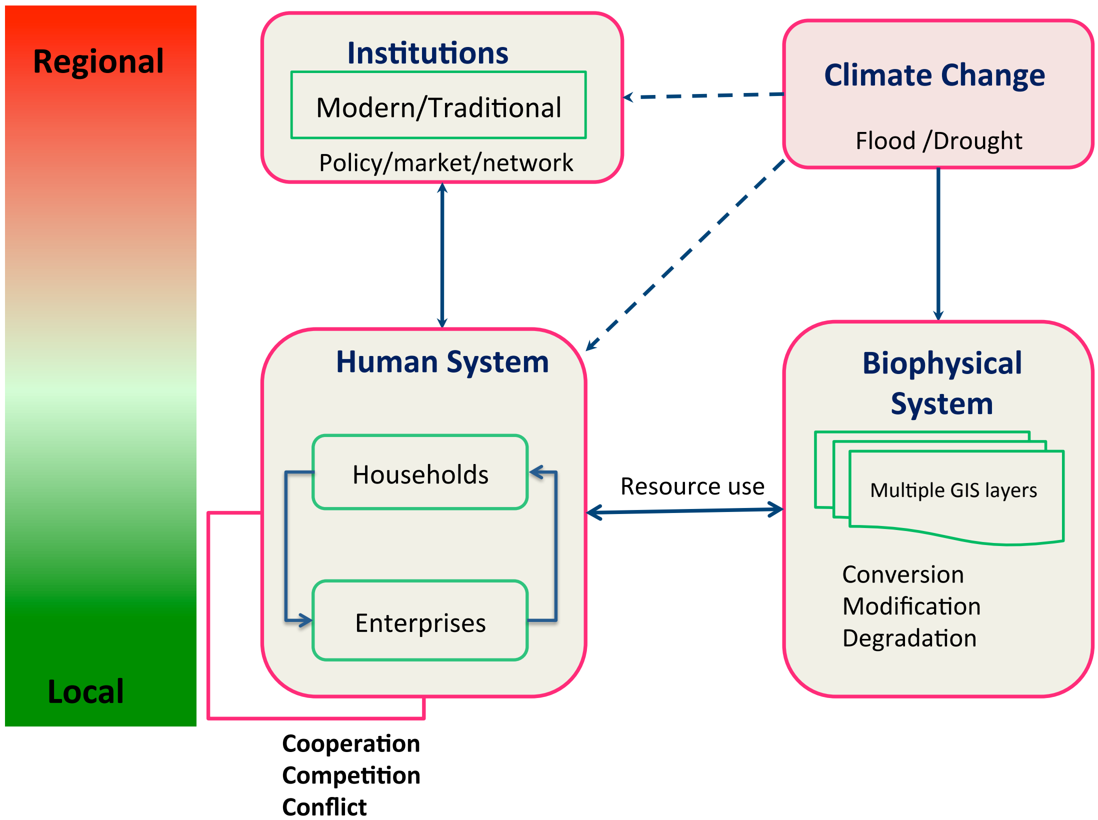


Figure 6: Conceptual representation of the South Omo zone

Our conceptual model demonstrates that the South Omo zone sub-system includes four major components: human system, biophysical environment, institution, and climate. The relation among the components emphasizes (i) the importance of considering the interaction of rural households and enterprises, (ii) the consequences of different actions of these actors on the land (biophysical environment) and feedback from it, (iii) the impact of climate change on the land, and (iv) the implication of institutional (i.e., governmental) policies on different actors and the land. The human system includes two major actors:

rural households and enterprise agents. These actors are land users in the system. The interaction among and between actors is influenced by resource use and function and the interaction can be of three types: cooperation, competition, conflict [14, 33, 82]. Depending on the assets and functions, the actors choose various livelihood strategies to enhance their chance of success in the system. Their action and intervention can influence the biophysical system, which comprises layers of attributes, in many ways. They can convert, modify or degrade the biophysical environment.

3.5 Model Implementation

The OMOLAND model comprises a set of inter-related components of the rural systems. The representation of these components and their interaction uniquely distinguishes this model from previously implemented agent-based models of rural systems (e.g., Bharwani et al. [23], Deadman et al. [45], Entwisle et al. [57], Le et al. [97], Lim et al. [98], Manson [107], Saqalli et al. [143]). The model is implemented in MASON [102], an ABM simulation toolkit written in the Java programming language, primarily designed to facilitate the development of fast and efficient ABMs. MASON provides extensive libraries to integrate GIS data (vector and raster) [150]. The model implementation is carried out in three phases. As shown in Figure 7, the modeling phases start with Theme 1 by considering the interaction of households, climate and biophysical environment. In the second phase, enterprises are added on top of Theme 1 to analyze issues raised in Theme 2. In the final phase, more complexity is added to the model by introducing institution to the system to address issues raised in Theme 3. Hence, the final phase represents all components of the OMOLAND model.

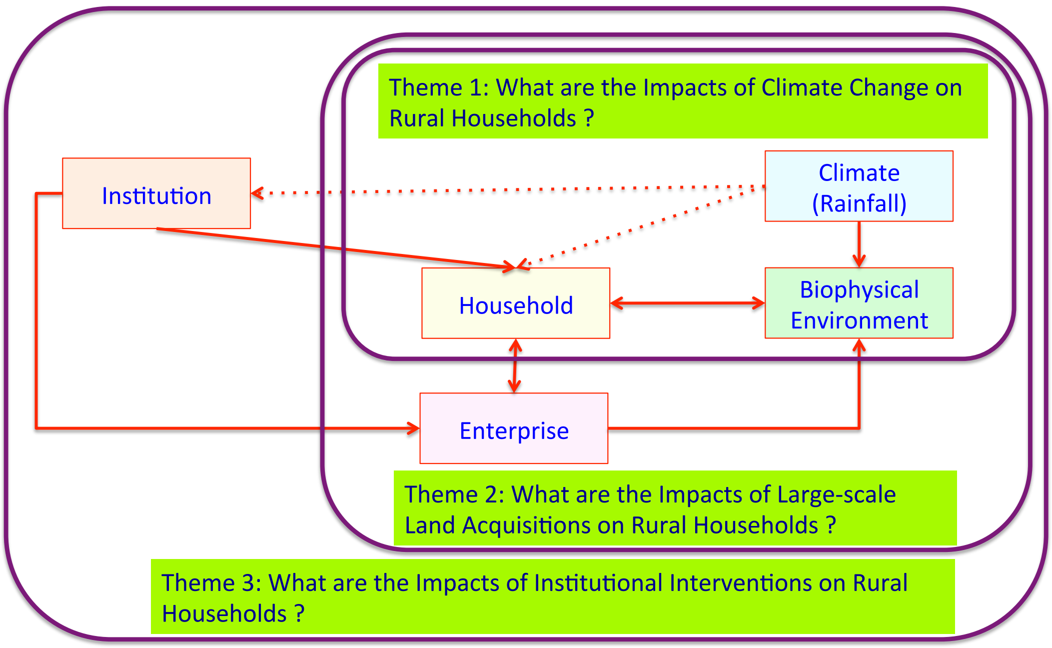


Figure 7: Model development phases

3.6 Model Description

A detailed description of the model will be given below. The description will follow the standard ODD protocol (overview, design concepts, and details) [75, 76].

3.6.1 Overview

3.6.1.1 Purpose

The purpose of the model is to investigate the sustainability consequences of large-scale land acquisitions in the South Omo zone, given a range of scenarios of regional climate change, and economic and policy changes.

3.6.1.2 State Variables and Scales

The OMOLAND model focuses on the interaction and decision-making of different actors in the system, especially the rural households, whose livelihood is highly coupled with climate and the biophysical environments [4, 21, 62, 69], the large-scale land enterprises who are newly introduced to the rural system [121], the impact of climate variability on the actors and the biophysical environment [6, 55, 67, 119], and the influence of these actors on their surrounding environment, and how the feedback from the environment influences the decision-making processes of the actors at different temporal and spatial scales [57, 87, 88, 99, 141]. Figure 8 illustrates the main components and relationships in the model using a UML (Unified Modeling Language) class diagram.

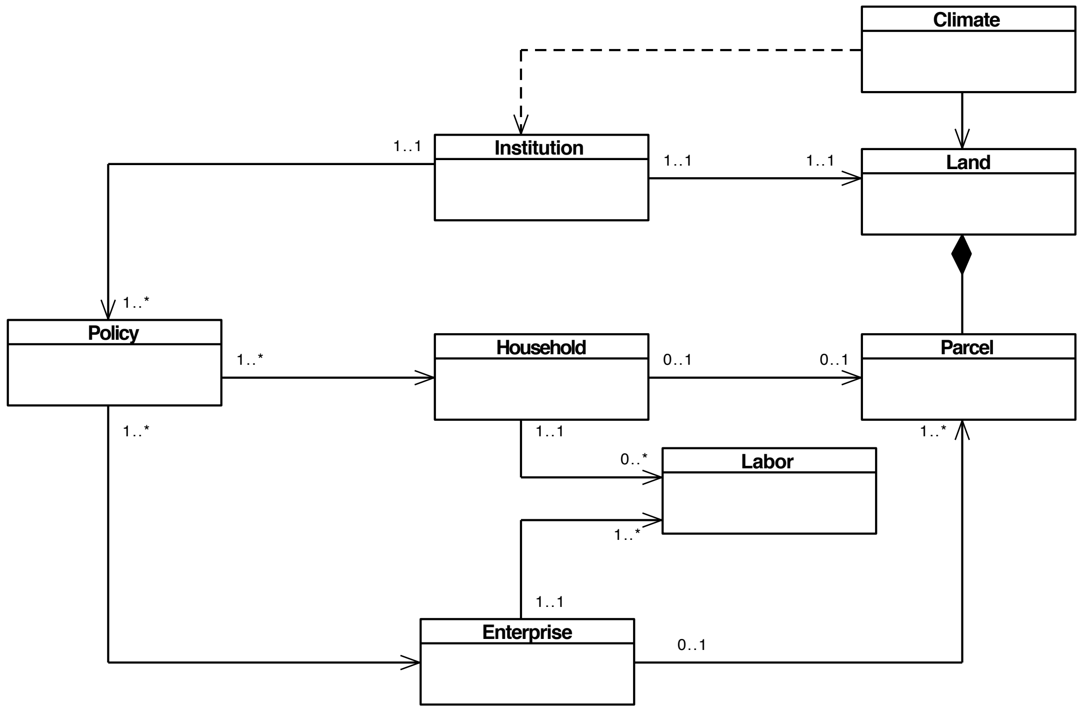


Figure 8: High-level UML diagram of the conceptual model

In the OMOLAND model, household agents can be considered the main agents in the system. Their different actions and interaction among themselves and with other components of the systems are modeled extensively as compared to enterprise and institution agents.

Household agents represent individual households that live in a subsistence agricultural system (herding and/or farming) within the study area as discussed in section 2.2.1. Household agents are heterogeneous in their profile, livelihood choices, and decision-making processes. They are bounded rational [145]. They do not have full knowledge of the environment but make decisions based on information they have at hand and on their previous knowledge. However, households learn, imitate skills and techniques, and make adjustments to their livelihood. They are also social agents, cooperating among themselves and competing with others for resources. Each household has one or more family members. Each family member tracks its own age and employment situation.

Enterprise agents represent business actors involved in a large-scale agricultural production system. They have a larger tract of land in their possession. They too are heterogeneous based on their land holding and the number of employee they can hire at a time. They create jobs to the rural system. They interact with household agents in a labor market as discussed in section 2.3.2.

The institution agent represents government, responsible for generating policies related to land utilization. The institution has overall knowledge of the entire area, determining and characterizing land for different uses. For instance, it assigns lands to enterprises based on land quality. The allocation to enterprises can be either on lands that are occupied or unoccupied by rural households. The institution agent can also relocate household agents depending on the demand for more lands from enterprise agents.

The environment represents the biophysical environment (both natural and built environment). It has a spatial extent of 146.7 by 224.7 kilometers (i.e., the South Omo zone). The environment is comprised primarily of heterogeneous parcels (built environment is minimal in this region, except for some roads) with a spatial resolution of a hectare (100 by 100 meters)[41]. The spatial resolution is defined based on the average land holding size of the rural households of the zone. Each parcel has quality that can be restored or depleted by the action of households and enterprises. The biophysical system dynamically responds to climate and its variation. Such response will indirectly influence landuse choices by households and enterprise agents.

Climate is represented primarily by rainfall in terms of precipitation distribution patterns and variations, calibrated to the study area. Climate variation includes patterns from normal to extreme events (e.g., drought, flooding). Climate determines the characteristics of biomass in the environment; i.e., biomass type, growth rate, productivity, and length of growing period. For a summary of all parameters and variables of the model see Table 3.

Table 3: Summary of input parameters and variables

Attributes	Parameters	Unit	Value or range of values	Reference
Global variables	Initial number of households		50000	*[2]
	Initial number of enterprise		100	
	Eviction policy status		true or false	
	Coverage of Adaptation Training	%	5	[84]
	Coverage of relief support	%	5	[84]
	Amount of relief support	kg/person/day	0.5	[84]
Attribute to Enterprise	Growth rate probability of enterprise		0	
	Maximum land allocated to enterprise	ha	100	
	Off-farm wage	birr[3]	7	
	Maximum number of labor required	person/ha	1	
Attribute to Household	Adaptation intention threshold		0.4	
	Adaptive household learning rate		0.05	
	Cognitive bias		0.2	
	Adaptation elasticity		0.2	
	Cost of adaptation		0.2	
	Risk elasticity		0.4	

[2]If reference are not listed, the values are of authors' estimation. These values are estimated mainly from field visit and author's estimation
[3]Birr is is the unit of currency in Ethiopia.

Attributes	Parameters	Unit	Value or range of values	Reference
	Percentage of initial number of adopter	%	5	
	Daily minimum expenditure	birr	2.5	
	Minimum labor age	year	11	
	Proportion of wedding dowry/inheritance		0.2	
	Birth rate		0.02	[41]
	Death rate		0.007	[41]
Attributes to herds/herding activity	Average price	birr/TLU	1600	
	Daily consumption rate	kg/TLU	3	[66, 144]
	Proportion of destocking rate		0.1	
	Livestock growth rate		0.0008	
	Daily maximum dry matter (DM) intake		7	[66, 122, 144]
	Maximum DM stored	kg	350	
	Proportion of restocking rate		0.1	
	Herd splitting threshold		0.3	
	Minimum vision range	km	50	
	Maximum vision range	km	200	
	Proportion labor to TLU	person/TLU	5	[122]
Attributes to farm/farming activity	Average initial farming cost	birr/ha	200	
	Farm Cobb-Douglas coefficient		0.5	
	Farm input cost	birr/ha	200	
	Farm labor efficiency factor		1.1	
	Irrigation farm cost	birr/ha	200	[92]
	Intensification status	true or false	true	
	Maximum days to wait after land preparation	days	30	

Attributes	Parameters	Unit	Value or range of values	Reference
	Minimum annual rainfall for crop production	mm	400	[8]
	Proportion labor to farmland (HA)	person/ha	0.7	
	Weeding day after planting	days	30	
Attributes to Vegetation	Base growth rate controller		2.39	[19]
	Minimum rainfall amount	mm	0.125	[66]
	Maximum vegetation per hectare	kgDM/ha	4000	
	Minimum vegetation per hectare	kgDM/ha	50	
Attributes to Climate	First drought year		5	
	First wet year		5	
	Frequency of drought years		5	
	Frequency of wet years		5	
	Steady state year status		true or false	
	Drought state year status		true or false	
	Wet state year status		false	
	Number of drought years	years	1	
	Number of wet years	years	5	
	Severity of drought		0.5	
	Severity of wet		0.5	
	Number of days with minimum rainfall	days	3	[130]
	Number of days with Minimum Effective Rainfall	days	15	[130]
	Minimum cessation rainfall threshold	mm	10	[130]
	Minimum Effective Rainfall (MER)	mm	40	[130]

Attributes	Parameters		Unit	Value or range of values	Reference
	Minimum days onset rainfall threshold		days	10	[130]
Attributes to Crop	Maize	Length of growing period	days	150	[8]
		Price	birr/kg	6	
		Yield	Kg/ha	3000	[8]
		Water requirement	mm/lgp	500 - 800	[8]
	Sorghum	Length of growing period	days	120	[8]
		Price	birr/kg	4	
		Yield	Kg/ha	1500	[8]
		Water requirement	mm/lgp	450 - 650	[8]
	Wheat	Length of growing period	days	130	[8]
		Price	birr/kg	9	
		Yield	Kg/ha	1200	[8]
		Water requirement	mm/lgp	450 - 650	[12]
	Teff	Length of growing period	days	100	[12]
		Price	birr/kg	12	
		Yield	Kg/ha	600	[12]

Attributes	Parameters		Unit	Value or range of values	Reference
		Water requirement	mm/lgp	750	[12]
Observer Parameters	Write output statistics			true or false	
	Write grid timer frequency			365	

The temporal resolution of the model is modeled as discrete time step in which each model step represents a day. Although the temporal resolution is a fine resolution, some processes may happen only when the necessary conditions are satisfied. For instance, crops can only instantiate and grow when a household agent sows crop seeds on his farmland. In the same manner, the age of a member of the household increases only once in a year.

3.6.1.3 Process Overview and Scheduling

The model sequence routine includes all the components which are involved in the scheduling routine. Each procedure is activated by the responsible actor or entity and at each time step, similar sequential procedures are activated in the same order. First, climate is updated. In this time, rain falls on each parcel. Then each parcel updates its soil moisture level with equal amount of the rainfall on a parcel. In our model, there is no overflow, inflow of water, or accumulation of soil moisture for simplicity reason. Therefore, the update mechanism is relatively simple. If there is no rain in a given day, the amount of soil moisture of a parcel is assigned as zero; otherwise the soil moisture of the parcel is the amount of rain on the parcel. After the update of the rainfall, the vegetation subroutine is executed. In each parcel where there is vegetation, vegetation will grow or shrink relative to the amount of moisture available in the parcel [6, 67].

The second routine is the household agent's routine. In each time step, each household agent engages in livelihood activities, updates profiles, and assesses success or failure of his actions. As shown in Figure 9, the main sequential procedures of the household are prediction of future climate conditions, analyses of adaptive response, selection of potential livelihood options, allocation of resources implementation of livelihood-related activities, monitoring wealth status, updating profile, and updating memory. The routines are only executed in the appropriate time when appropriate conditions are fulfilled. For instance, sequential procedures from prediction of future climate condition to determination of livelihood option are executed once in a season. At the prediction date, the household determines the onset and amount of rainfall of the upcoming season. Based on the outcome of their action, each household makes an appropriate decision to either adapt or fail to adapt in response to the anticipated climatic condition of the season. Depending on the adaptation decision, each household determines the best livelihood or combination of livelihoods (herding, farming, and off-farming), which yield the highest return. The household then allocates the necessary resources to each livelihood option proportional to the share value of each livelihood option. The household remembers its decision and allocation of resources for each livelihood option throughout the implementation of each activity. Implementation of activities is carried out until the activity has either been discarded or completed. Update of memory is executed at the end of each season.

The livelihood activity sequence of each household is scheduled in the following order: herding, farming, off-farming. If a household only engages in one of the three livelihood options, it only implements the corresponding activity sequence. For instance, herding activities are invoked if the household has livestock. A household with livestock looks for high quality grazing areas for its herds. The household also monitors its herd income in this sequence. Households with farmland implement farming activities. The farming activities include land preparation, planting, weeding, and harvesting, and each activity is invoked in this sequence. The implementation date of each activity is determined when the necessary conditions are fullfiled., for instance, after the onset of rain, a household assesses if there is sufficient moisture to perform planting activity. Likewise, when the crop is ready to harvest, a household execute harvesting activity. At the time of the harvest, the household updates its income proportion to the yield harvested. Finally, the household agent excutes any off-farm activities, which can be either continuing work on his current off-farm activity or searching for a new off-farm opportunity.

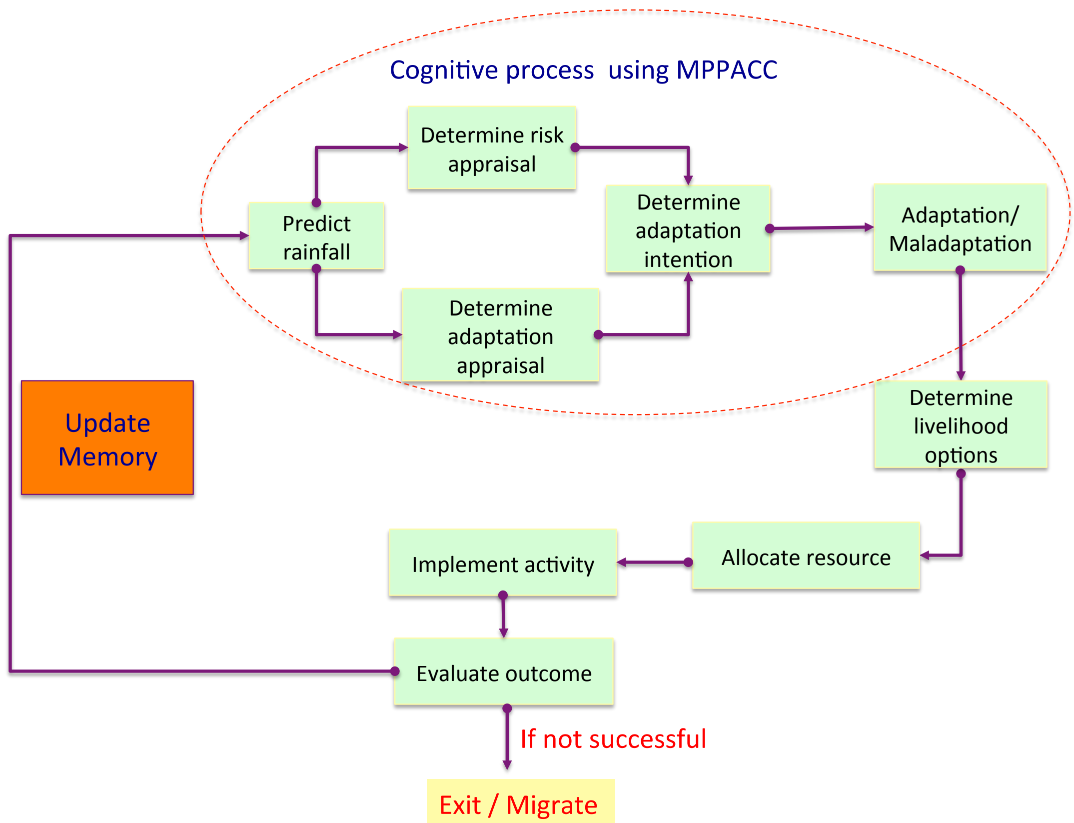


Figure 9: Household sequence in OMOLAND

After the household routine, herd sequence is invoked. Herds consume grasses from their current location and move to the assigned location. They update their metabolic rate, food level, and their size based on the grass that they consume.

Following the herd sequence, crop sequence is invoked. Crop is activated only when it is planted. Similar to vegetation, crop responds to the available moisture in the parcel by either growing or shrinking. In each time steps, crop updates its growth and production level.

The next procedure is enterprise routine. In each time, enterprise agents will manage labor force, determine to recruit or dismiss workers (daily laborers), and act on their respective decisions. Each enterprise determines the amount of labor required and allocates the required resource to the task. If the current labor is more than required, the enterprise agent minimizes the labor force by dismissing extra workers. In the same manner, if there is a need for more labor forces, the agent searches for extra labor and hires to fill the labor gap.

After the enterprise routine, the institution sequence is invoked. The institution agent selects potential households that need capacity building training or relief support and provides the necessary support. Finally, an observer object, which manages gathering of statistics, is invoked and all the output is written on a disk.

3.6.2 Design Concepts

3.6.2.1 Observation

The OMOLAND model displays a suite of simulated data panels of the Graphic User Interface (GUI) as shown in Figure 10. The visualization panel displays the current landuse pattern, the location of households, and herd movements. A separate GUI display is also available to observe the spatial and temporal variation of rainfall and vegetation growth. Different types of statistical outputs are also computed, collected, and displayed in the GUI panel. Although many detailed statistical outputs can be collected and saved onto disk, the statistical output on the GUI display provides information at run time in order to observe the model's behavior according to a useful dashboard. At the global level, the main statistics collected and displayed on the GUI panel include household age distribution, household family size, household income source, wealth distribution, crop growth, parcel rainfall, household onset prediction, household rainfall amount prediction, percentage of household who are implementing climate change adaptation options, and average household climate change adaptive capacity. The visualization of the model can also be used as means of model verification ("visual debugging")[74].

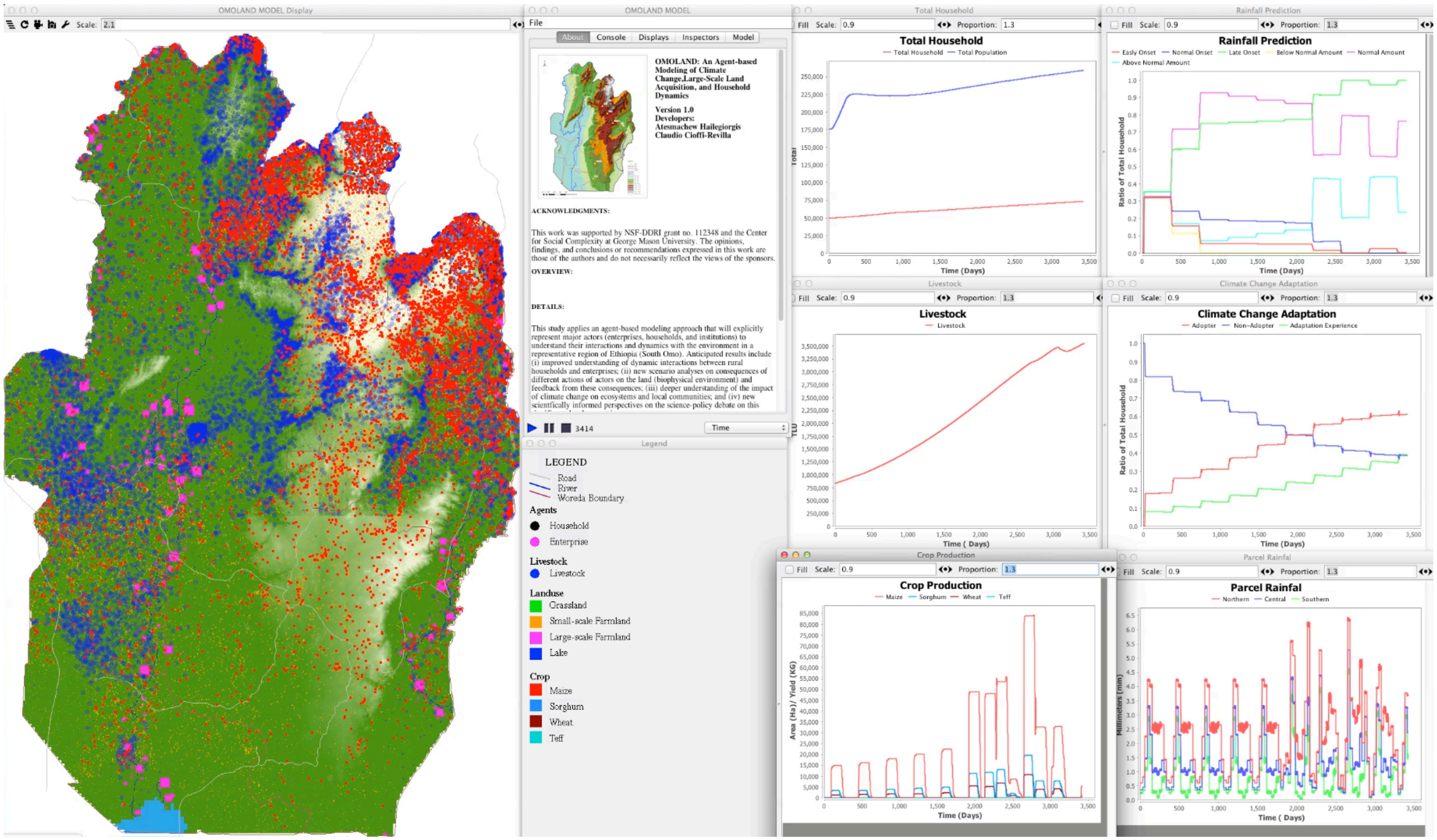


Figure 10: Model Panel Diagram

3.6.2.2 Sensing

In the OMOLAND model, agents sense their environment and react to change. Rural households make predictions of the future climate conditions based on their experience and anticipation and make their best judgment. Households that have livestock react to the change of vegetation and take their livestock toward the best pasture in their vicinity [6, 67]. In the same manner, households that practice farming also sense the dynamics of environment processes such as soil fertility and moisture availability and make the necessary decision to produce crop yield. In the current state of the model, enterprise interaction with the environment is relatively simple. It is randomly invoked on runtime. Depending on the assigned threshold, an enterprise agent senses the need for recruiting or dismissing labor and acts accordingly.

3.6.2.3 Interaction

Interaction between agents and the environment is one of the main strengths of the OMOLAND model. OMOLAND captures multi-scale interaction within and between different entities of the model. Interactions represented in the models are household-household, household-enterprise, household-institution, enterprise-institution, and household-environment interactions. Household-household interactions are of two kinds: intra-household and inter-household interactions. Intra-household interaction is mainly represented as resource-sharing within households. Member of the household contribute labor, knowledge, and any income generated from their specific activities. Inter-household interaction represents the interaction between different households in relation to information-sharing, and competition for resource.

Household-enterprise interaction takse place in the labor market. Although in reality there are interactions among enterprises, such interaction is not explicitly represented in the OMOLAND model. The representation of complex enterprises is beyond the scope of this study, as the main focus of this study is to understand the dynamic interaction of rural households and enterprises. This simplification of reality helps us to keep the model as simple as possible by avoiding further complexity.

Another interaction represented in the model is the interaction of both households and enterprises with institutions. The institutions interact with rural households and enterprises by providing information and incentives, which might have greater impact on the decision-making processes of these agents.

As the economic system of rural households and enterprises is highly coupled with environment, there is strong representation of interaction between agents with their environments and vice versa. Household agents interact with the environment directly when they engage in farming or indirectly when they manage their livestock. Households can change the properties of the land as they convert it from grazing to farmland. Enterprises interact with the environment by changing the properties of the land to farmland but do not perform detailed production activities per se.

3.6.2.4 Stochasticity

The model contains stochastic behavior. Stochasticity is mainly introduced as a random seed in the selection criteria and decision-making of agents in their daily activities. For instance, in predicting the future climatic situation, agents depend on their previous experience. However, since agents have a short memory of climatic situation of previous years, their predictions are highly subjective. Such phenomenon are captured by adding noise in agents' prediction analysis as discussed in section 3.6.3.3.3.

3.6.2.5 Emergence

OMOLAND captures different emergence phenomena. Emergent phenomena in this context are any macro level patterns or outcomes generated from the interaction of agents and environment at the micro level. Emergence Household livelihoods change, types of climate adaptive responses, behavrioral change on the outlook of future climate situation, household mobility (migration), and landuse changes are some of the expected emergent phenomena.

3.6.2.6 Adaptation

Households adapt to the change in climate and their surrounding environment. Households adjust their livelihood choice and resource allocation based on the current climatic condition, experience, and availability of resources. Such adjustments could influence their activity selection and their subsequent decision-making processes as discussed in section 3.6.3.3.3. Households' choice of more productive grazing land can also be considered as an adaptation to environmental change.

3.6.2.7 Prediction

There is a sense of prediction in the model. Each season, each household that want to engage in an agriculture production system makes prediction of rainfall pattern of the upcoming season. Based on the prediction, each household makes necessary preparation and adjustment to implement faming and/or herding activities as discussed in section 3.6.3.3.3.

3.6.3 Detail

3.6.3.1 Initialization

The model is designed to provide flexibility to assign initialization values, so that the model initialization is set by model parameters defined by the user at the beginning of each simulation. In normal circumstances, the model runs with default values generated from stylized data. At the initialization, the location of households on given parcel cells is assigned based on density distribution. We utilize Landscan population data to generate a density distribution surface. The parcel with the highest density value is given priority as a potential household location over the parcel with the least density value. The attributes of each household, such as ethnic identity, family size, herd size, number of farmlands, and stored capital, are given randomly from a distribution generated from stylized real data. Enterprises are randomly assigned mainly in areas where irrigation is possible. The attributes of enterprises are also assigned randomly within the assigned thresholds parameters.

3.6.3.2 Input

The spatial components of the model are read as an input from a file stored in a Comma Separated Value (CSV) files. The spatial data were pre-processed in ArcGIS before utilizing as an input in the model. Parcel quality data is generated by combining landuse (based on NDVI of MODIS-TERRA dataset [101]) and soil data (based on FAO world soil dataset [61]). The elevation and slope are generated by esampling the 90 meters DEM of SRTM dataset [89]. The climate data is based on 109-year monthly precipitation data (1900-2009) of the historical rainfall data (CRU-TS v3.10.01) at 0.5 degree spatial resolution (approximately 55 kilometers) on land areas from the CGIAR-Consortium for Spatial Information (CSI) database [42]. The data was orginally developed by the University of East Anglia (UEA)'s Climatic Research Unit [139]. Since in the South Omo zone the mean daily temperature is relatively constant, the representation of climatic condition is based on the variability of daily rainfall. The daily rain is generated from monthly precipitation data. To make it tractable, the monthly rainfall data is distributed equally in each day of the month. A similar simplification was also made on spatial distribution of the rainfall. All parcels that fall in a 0.5 by 0.5 latitude/longitude of the rainfall pixel receives an equal amount of rain. In the model, the distribution of rainfall is used as a proxy for estimating the amount of moisture that might be available in the soil pertinent to estimating crop and vegetation growth. These data were also used to determine the spatial extent and the pixel resolution of the model.

3.6.3.3 Submodels

The OMOLAND model incoporates different submodels. We discuss the characterstics of each submodel in detail in the following sections.

3.6.3.3.1 Climate Submodel

The climate submodel captures different climate indices that are pertinent to this study. As the main economic activities in the South Omo Zone are highly dependent on a rain-fed agriculture system as discussed in section 2.2, climate indices such as rainfall onset, cessation, and amount are important. Hence, these concepts are included in the model and will be described in detail below.

Onset Date

Onset date is one of the most critical factors for rain-fed farming systems. Reliable prediction of onset time will greatly assist on-time preparation of farmlands, mobilization of manpower and equipment, and will also reduce the risks involved in planting too early or too late. However, determination of exact onset date is still a challenge, especially in areas where irregularity of rainfall distribution is a common phenomenon. One of the most common ways of determining onset date is by analyzing the intensity and duration of rainfall in a given season [129, 130]. According to Omotosho et al. [130], onset is defined as "the beginning of the first two rains totaling 20 millimeters or more, within 7 days, followed by 2-3 weeks of each with at least 50% of the weekly crop-water requirement" [130]. This definition captures two main features of rainfall: intensity and duration. The rainfall intensity or amount indicates the beginning of the rainy season and its continuation of rain through the season while the duration indicates the importance of moisture in the first 28 days, which are most critical for seed germination and crop establishment.

It is important to mention that one of the challenges of the above definition is its effectiveness in arid and semi-arid areas where rain-fed farming is rare and herding is the dominant agricultural practice. Onset is important for pastoral communities, too. It influences movement patterns of pastoral communities, especially to and from their camping sites. However, the amount of rainfall necessary to determine onset in the context of pastoral communities needs to be related to the amount of moisture necessary to grow vegetation (grass). Given the need to incorporate both farming and herding practices in our model, we introduce a spatial index factor that captures the variation of onset in arid and semi-arid area. In arid areas, onset is determined based on the minimum moisture requirement for grass growth while in semi-arid areas onset is determined based on the minimum moisture requirement for crop germination.

Using the above modified onset definition, we determined the mean onset of the South Omo zone using 109-years (1901-2009) of rainfall data. This onset is considred as a reference onset and is used as an input in the model. Each season, onset is calculated based on the above modification for each parcel and compared with a long-term mean onset whether the current onset is observed early, on time, or late, based on the following equation.

$$O_c = \begin{cases} EO, & if\ O < O_m - w \\ LO, & if\ O > O_m + w \\ NO, & otherwise \end{cases} \tag{3.1}$$

Where O_c is the current onset category, O is the observed onset date, O_m is the mean onset date of the season, EO is "Early Onset," LO is "Late Onset," and NO is "Normal Onset," w is a margin parameter indicating a change from the normal onset date. We consider 15 days (two weeks) gap from normal onset to characterize the early and late onset categories. If the current season is earlier than the mean by a margin of 7 days, it is considered as "Early Onset." If the current onset occurs later than the mean onset by a margin of 7 days, it is considered as "Late onset." Otherwise, it is considered as "Normal Onset."

Cessation Date

Cessation of rainfall is another essential component in rain-fed agriculture systems. Cessation date indicates the end of the rainy season. Omotosho et al. [130] defined cessation as "any day from the onset when there are 15 or more consecutive days with a rainfall amount less than 50% of the crop–water requirement." Omotosho et al. [130] suggested that to avoid fault dry spell that might occur within the season, a reasonable delta value (at least a minimum of 72 days) after the onset date is necessary to determine the cessation. Similar to onset, a mean cessation date was calculated using the mean rainfall data of 109-years and used as an input to determine the cessation date of each season. The cessation is also categorized into three classes: early, normal, and late cessation. It is determined as:

$$C_c = \begin{cases} EC, & if\ C < C_m - v \\ LC, & if\ C > C_m + v \\ NC, & otherwise \end{cases} \tag{3.2}$$

Where C_c is the current cessation category, C is the observed cessation date, C_m is the mean cessation date of the season, EC is “Early Cessation,” LC is “Late Cessation,” and NC is “Normal Cessation,” and v is a margin parameter indicating a change from the normal cessation date. We consider the default value of v as 7 days (one week).

Length of Growing period

The length of the rainy season or growing period is the number of days between the observed onset and cessation date of the season. It is calculated as follows:

$$LGP = C - O \tag{3.3}$$

Where LGP is length of growing period, C is date of cessation, and O is date of onset of rainfall.

Amount of Rainfall

The total amount of rainfall in the season is also calculated to determine the moisture level of the season. It is calculated by summing up the amount of rain of each day in the LGP. It can be represented as:

$$r = \sum_{i=O}^{C} r_i \tag{3.4}$$

O is the onset date, and C is the cessation date; r_i is amount of rain in each day, and r is total amount of rain in a season.

As rainfall is the main source of moisture for the production system in the zone, a variation from the normal amount can affect the agricultural practice of rural households. Excess moisture, particularly in the lowlands area, where moisture is a constraint, enhances grass growth. In the contrary, in the highland area where there is sufficient moisture for farming, moisture in excess of the normal might affect crop production by creating waterlogging or flooding. The variation of rainfall amount of each season from the long-term mean (based on 109-years rainfall data) is determined in each season and categorized into three ordinal scales, namely, below-normal, normal-amount, and above-normal. It is defined as follows:

$$A_c = \begin{cases} BN, & if\ r < r_m - x \\ AN, & if\ r > r_m + x \\ NA, & otherwise \end{cases} \tag{3.5}$$

Where A_c is current rainfall amount category, BN is “Below Normal,” AN is “Above Normal,” and NA is “Normal Amount,” r is the total amount of rainfall in the given season, r_m is long-term mean rainfall amount of the season, and x is a parameter indicating the change from the long-term mean rainfall amount.

3.6.3.3.2 Vegetation Submodel

The vegetation submodel focuses mainly on grass growth. Grass growth is highly dependent on the amount of moisture and the soil fertility. In this study, only rainfall is considered as the main factor that influences grass growth and dry matter (DM) production but covers the influence of soil and other factors by using elevation and NDVI as a proxy. The vegetation level in a given parcel at a given time t is determined as:

$$V_t = V_{t-1} + V_{gt} \tag{3.6}$$

$$V_g = \psi \gamma R_f V \tag{3.7}$$

$$R_f = ar^3 + br^2 + cr + d + \varepsilon \tag{3.8}$$

$$\varepsilon = \delta * ndvi_{residual} \tag{3.9}$$

$$\gamma = \frac{0.009}{0.009 + \left(\frac{elev - elev_{min}}{elev_{max}}\right)^3} \tag{3.10}$$

$$V = 1 - \frac{V_{t-1}}{V_{max}} \tag{3.11}$$

Where V_t is vegetation at time t, V_{t-1} is vegetation at time $t-1$, V_g is growth level at time t, R_f is Moisture Index , V is Vegetation Index, ψ is vegetation growth rate parameter, γ is Elevation Index, and r is daily rainfall amount. These indexes determine the amount and rate of grass growth in a given parcel. The moisture index is developed based on the NDVI and rainfall, and parameters a, b, c, d are generated from a regression analysis of NDVI and rainfall of the study area. The elevation index is used as a proxy for shrub and tree competition and its value is inversely proportional to elevation. This is mainly due to the fact that in high moisture areas, trees and shrubs compete with grasses and inhibit the growth of grasses. The vegetation index controls the rate of growth in which igrows quickly when it is at minimum level but grows more slowly as it approaches the maximum.

3.6.3.3.3 Household Submodel

Household submodel processes is the core of the model. This submodel captures household agents' adaptive behavior and decision-making processes, and their interaction with other household agents, with enterprises and their surrounding environment.

Socio-cognitive Processes

Several studies have been devoted to characterizing factors that influence the capacity of rural communities to adapt and their priority for adaptation measures [3, 26, 147, 158]. These studies emphasize the importance of natural resources and socioeconomic determinants, such as wealth, technology, information and skills, infrastructure, institutions, and equity, in shaping the adaptive behavior and the mechanism in which rural communities respond to climate variability. Indeed, Deressa et al. [49] also provide a similar assessment after analyzing factors that determine the choice of adaptation strategies in crop production systems in the Nile basin of Ethiopia and indicate that factors such as education, income, and access to information and credit enhance adaptation.

Although socioeconomic factors are instrumental in better understanding the way rural communities respond to climate-induced propensity, the role of cognition in adaptation to climate change has so far been largely neglected [77, 94]. Smith et al. [149] suggested that adaptation strategies depend not only on present households' characteristics and the surrounding biophysical environment but also by previous experience and the networks to which they belong. Indeed, Grothmann and Patt [77] argue that people's beliefs about risks, chances, and adaptation options drive much of the process of adaptation to climate change. In addition, the individual's perception of the event and its subsequent ability to manage, adapt to or escape from its impacts affects the adaptation strategy chosen. The timing of response to climate-induced stimuli can be either proactive or reactive. In many cases, individuals who respond to climate variability based on prior information such as climate prediction and seasonal rainfall forecast tend to apply a proactive approach to adaptation [149].

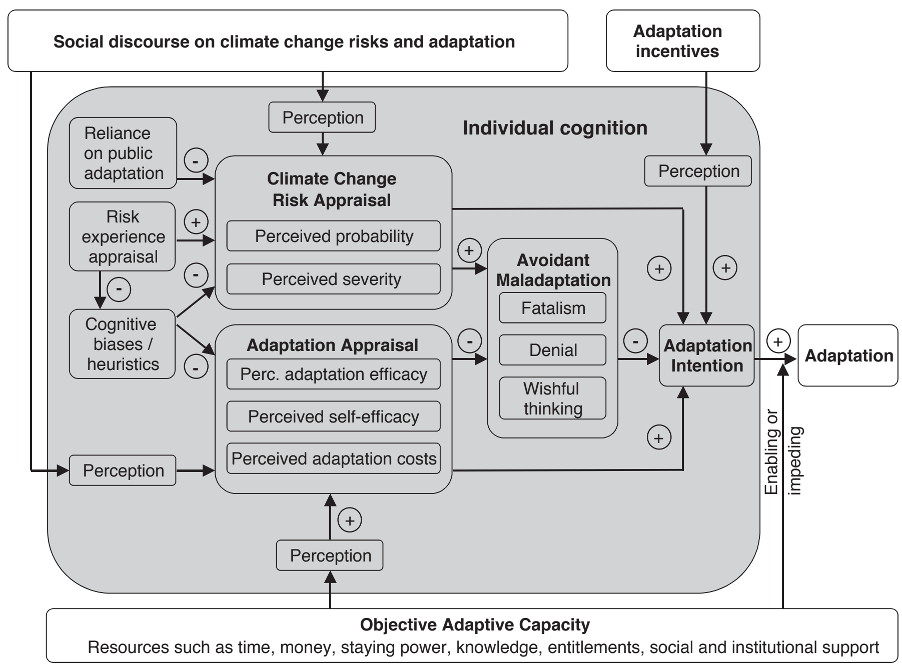


Figure 11: Model of Private Proactive Adaptation to Climate Change (MPPACC) (Following Grothmann and Patt [77])

A comprehensive approach that captures subjective adaptive capacity is the Model of Private Proactive Adaptation to Climate Change (MPPACC) proposed by Grothmann and Patt [77] as shown in Figure 11. The model not only provides insights into people's perceptions of climatic impacts but also broadens the analysis to include perceptions of their own capacity to adapt to change, which is often overlooked in conventional adaptation studies. Moreover, the model, based on the original Protection Motivation theory developed by Maddux and Rogers [105] to understand cognitive processes, which mediate adaptive/maladaptive behavior towards health threats, has been extended and applied to various fields ranging from journalism to the environment [95].

The MPPACC framework has been applied in different climate change studies. Grothmann and Patt [77] applied their framework in two very contrasting environments to assess the validity of the MPPACC framework. They assess rural households' decisions to change farming practices to adapt to predictions of seasonal rainfall in Zimbabwe. They also assess the variance in households' long-term precautionary action to avoid flood property damage in flood-prone areas of Cologne, Germany. Both case studies deal with people's adaptive responses to the risk of extreme events and information about climate variability. Indeed, Kuruppu and Liverman [95] applied the MPPACC framework to investigate the motivation of rural households to adapt in anticipation of climate change through pilot community projects in Kiribati. Kuruppu and Liverman highlight the importance of implementing a cognitive model to gain a greater insight on individual's adaptive capacity. Although the MPPACC framework incroporates many important features, the framework has not yet used in agent-based modeling context. However, its potential for ABM has been highlighted[93, 94, 149] Hence in this dissertation, we adopt the key element of MPPACC to capture socio-cognitive processes of households and structure our analysis.

Climate Forecast

We begin the implementation of MPPACC by framing the way individual households perceive future climatic conditions for proactive adaptive response. Perception of future climatic condition is based on the availability of accurate forecasts and dependent on the level of trust an individual places in the information [159]. Two climate indices, onset and amount, are the main focus of these processes. Households that are entirely or partially dependent on rain-fed livelihood predict the future rainfall pattern based on their experience and information they might get from their neighbors or public media. In the current version of the model, households predict based only on their past experience of the rainfall pattern in their environment and proactively respond to possible impacts of climatic variability

We assume that households have short memory. They have the capacity to remember limited number of years of climatic conditions. Their decision is influenced more by recent events than by past events when they forecast the condition of future climate.

Based on their past experience, households predict current onset as follow:

$$O_c = max \sum_{i=1}^{n} \sum_{j=1}^{m} O_i \beta_i + \varepsilon \tag{3.12}$$

Where O_c is the current onset, O_i the onset at year i, β_i is the weight given for onset at year i, n is the number of ordinal category (EO, NO, LO) of onset, m is the number of years the household can remember, and ε is a stochastic error term.

Similarly, the current amount is determined as:

$$A_c = max \sum_{i=1}^{n} \sum_{j=1}^{m} A_i \psi_i + \varepsilon \tag{3.13}$$

Where A_c is the current amount, A_i the onset at year i, ψ_i is the weight given for amount at year i, n is the number of ordinal category (BN, NA, AN) of amount, m is the number of years the household can remember, and ε is a stochastic error term.

The value of O_i and A_i is a binary, 0 or 1. The above equation works as follow. If the household wants to determine the rainfall amount and if the amount in year i was registered as NA , the A_i for year i, the NA will be assigned as 1, and the other indices (BN and AN) will be assigned as 0.

Risk Appraisal

In the MPPACC framework, the risk appraisal is determined based on two factors: perceived probability and perceived severity. Perceived probability indicates the person's expectancy of being exposed to threat, while perceived severity is the person's appraisal of how harmful the consequence would be if the threat actually happens. As it is suggested by Grothmann and Patt [77] to include the two components for determining the risk appraisal of individuals, effort has been made to explicitly represent both components in determining the risk appraisal of households. The perceived probability is determined based on the confidence level of the household prediction of the current rainfall pattern. It focuses on determining how frequently the current onset and amount occurred in the past years. The probability of both indices is determined based on the confidence level or intensity of the current onset and amount as discussed in section 3.6.3.3.3. Therefore the intensity or probability of current onset is calculated as:

$$I_o = \sum_{i=1}^{m} O_i \beta_i + \varepsilon \tag{3.14}$$

Similarly, the intensity of the current amount is given as:

$$I_A = \sum_{i=1}^{m} A_i \psi_i + \varepsilon \tag{3.15}$$

By combining the intensity or probability of current onset and amount, we determine the perceived probability as:

$$P = qI_O + pI_A \tag{3.16}$$

Where P is perceived probability, q and p indicate the influence of onset intensity and amount intensity.

The perceived severity is determined based on the potential impact of the current climate pattern on agricultural practices. In the model, the value of perceived severity, S , is fixed and considered as a parameter. The value includes the effect of onset and amount of rainfall on agriculture system as shown in Table 4. We estimate the values based on literature review [6, 55, 67, 68, 111, 128].

Table 4: Severity of onset and amount on agriculture production

Onset	Amount		
	Below Normal	Normal Amount	Above Normal
Early Onset	Medium (0.4 - 0.6)	Very low (0 - 0.2)	Low (0.2 - 0.4)
Normal Onset	High (0.6 - 0.8)	Low (02 - 0.4)	Low (0.2 - 0.4)
Late Onset	Very high (0.8 - 1.0)	Medium (0.2 - 0.4)	Medium (0.2 - 0.4)

After calculating the perceived probability, we determine the risk appraisal by combining the perceived probability and severity if the current onset and amount happen and calulated as:

$$RA = 1/(1+\exp(-a(P*S-\zeta))) \tag{3.17}$$

Where RA is risk appraisal, S is perceived severity, and P is perceived probability, and ζ is risk elasticity parameter.

Adaptation Appraisal

Adaptation appraisal comprises three subcomponents: perceived adaptation efficacy, perceived self-efficacy, and perceived cost efficacy. Perceived adaptation efficacy indicates the belief of a household in the effectiveness of adaptive measures it is going to apply to avert any threat that may occur [77]. Perceived adaptation efficacy is usually measured based on household' characteristics such as age, sex, income, education level, access to technology, and household size. Several studies [49, 115, 125] have indicated that among other factors, household size, age of the household head, wealth (both monetary and livestock size), and access to technology play a significant role in determining the adaptive capacity of rural households in most African countries in general and in Ethiopia in particular. In this model, these determinants are used to determine the perceived adaptive efficacy of rural households as follows:

$$AE = aAge + bSex + cHHSize + dAccess + e + \varepsilon \tag{3.18}$$

The value of AE is between 0 and 1, in which 0 indicates less adaptive efficacy while 1 indicate high efficacy. The coefficients (a,b,c,d) and the constant term e are estimated based on literature.

Another component of adaptation appraisal is perceived self-efficacy. Perceived self-efficacy indicates the person's perceived ability to perform or carry out these adaptive responses. The perceived self-efficacy relates particularly to a household's past experience in responding to climate variability. An individual develops self-efficacy through experience or through learning [77, 91]. Individual self-efficacy is calculated as:

$$SE = aExp + \varepsilon \tag{3.19}$$

Where SE is the perceived self-efficacy, a is a parameter indicating the significance of experience, Exp.

Individual perception of cost of implementation of adaptation measures is another factors that affects the adaptation appraisal. Grothmann and Patt [77] define perceived cost efficacy as "the cost for applying the adaptive responses." Adaptation cost directly related with objective cost mainly related to implementing agriculture production. For instance farming costs include labor, fertilizer, high-yield variety seed, and land. In case of herding, the costs can be labor and veterinary cost. To change their productive system as an adaptation measure, a household should have the capacity to implement any adaptive measure. Since in OMOLAND households can practice both farming and herding at the same time, we developed a marginal cost of both activities. In order to implement adaptation measure, households should perceive that they have the capacity to cover the cost. The perceived cost efficacy is given as:

$$CE = 1 - \left(\frac{0.12}{0.12 + \left(\frac{Cost_{Expected}}{Wealth} \right)^3} \right) \tag{3.20}$$

Where CE is perceived adaptation cost. The $Cost_{Expected}$ is the expected total input cost for farming and/or herding if the household want to implement any new activity.

According to Grothmann and Patt [77], increase in perceived adaptation and perceived self-efficacy increases adaptation appraisal while increase in perceived cost efficacy decreases the adaptation appraisal. In the model the adaptation appraisal is calculated as:

$$AA = \alpha AE + \beta SE - \gamma CE \tag{3.21}$$

Where AA is the adaptation appraisal, AE is perceived adaptation efficacy, SE is perceived self-efficacy, CE is perceived cost efficacy, and α, β, γ are coefficient indicating the significance of each variable.

Adaptation Intention and Decision

One of the strengths of the MPPACC model is that the model explicitly distinguishes between intention and actual behavioral adaptation. Adaptation intention focuses on individual intent to adapt while behavioral adaptation shows the actual implementation of adaptation measures by the individual. According to Grothmann and Patt [77], before an individual chooses to employ an adaptive response he first forms a decision or intention to take these actions. Adaptation intention is realized when an individual considers the consequence of both risk appraisal and adaptation appraisal. It is calculated as:

$$AI = \frac{1}{1 + exp\left(-b\left(\eta RA * AA - \xi\right)\right)} \tag{3.22}$$

Where AI is adaptation intention, η is a parameter indicating the intensity of cognitive mediation processes , ξ is cognitive bias parameter, and b is exponential parameter.

The level of adaptation intention indicates the commitment of an individual to perform any adaptation measure. Small intention realization indicates a lack of objective adaptive capacity of an individual while large intention realization indicates the capacity of an individual to perform the adaptive measure. In our model, we set a threshold to identify the level of realization of intention of the household. Adaptation intention less than adaptation threshold parameter (Γ) is considered as maladaptation and if the intention is equal or greater than the adaptation intention threshold, a household will implement adaptation measures as:

$$Decision = \begin{cases} Adaptation, & if\ AI \geqq \Gamma \\ Maladaptation, & otherwise \end{cases} \tag{3.23}$$

One of the advantages of setting an adaptation threshold is the possibility of differentiating the objective adaption decision and the perceived adaptation decision. The objective adaptation decision is the real decision, which passes from perception to action. However, perceived adaptation may not be executed if the real cost of implementing is the adaptation measure beyond the capacity of the household.

The distinction between adaptation and maladaptation affects a household's response to future climate situations. In case of maladaptation, the adaptive measure is always similar. Households will continue to apply the same measure season to season. This is to say that those maladaptive agents will not realistically differentiate between the current climate condition and the normal climate condition. Due to their incapacity, they are always considering the climatic situation as "normal." They behave as though both onset and amount in each season are "normal" even when they are not. On the contrary, adaptive households consider possible alternative to minimize the risk of climate variability. They allocate resources, within the limit of their capacity, in line with climate variability.

Household Livelihood Options

In the OMOLAND model, households sustain their livelihood by engaging in any of the three livelihood options: farming, herding, and off-farming. The income generated from each activity is determined by the amount of household labor applied to each activity, household assets (farmland, livestock), off-farm opportunities, climatic conditions, and biophysical environment conditions. Households that allocate the necessary inputs for each livelihood option will get more return than those who do not. Below we will give the description of each livelihood, the type of activities that each livelihood demands, and how households make their decision to select the best livelihood combinations and allocate resources to execute activities in each livelihood options.

Farming

Farming livelihood focuses on crop production. It covers the processes from assessing the potential of the land for crop production to actual implementation of crop production activities such as land preparation, planting, weeding, and harvesting. Households that decide to engage in farming select the appropriate crop type that they want to plant. A household's choice of crops depends on its expectation of seasonal rainfall and their adaptation decision. The current prediction of onset and amount influence its expectation of timing and amount of seasonal rainfall. Each household estimates the expected rainfall amount moisture level of the season by comparing the current climate predication with the normal condition. Households that are conscious of climatic change make adjustments on their crop choice based on their expectation of future climatic condition. However, households that are not adaptive continue planting the same type of crop season to season. Grothmann and Patt [77] observed a similar situation in Zimbabwe in which maladaptive farmers prefered planting maize rather than sorghum in the drier seasons, even though sorghum is more drought-resistant and profitable than maize.

In our model, we consider four crop types, which are major crops in South Omo zone as discussed in section 2.2.1. They are maize, sorghum, wheat, and teff. Adaptive households choose the best fit crop or combination of crops (if they decide to diversify) out of these crop types based on their climate expectation, whereas maladaptive households continue planting the same crop type, as their expectation of climate is “normal” climatic condition.

There are four main farming activities: land preparation, planting, weeding, and harvesting. Each household agent who engages in farming activities performs these tasks sequentially. In order to accomplish these tasks and allocate the required resources, households need to determine the date for executing each activity.

The farmland preparation date is determined based households’ expectation of onset of rainfall. Land preparation is performed before the onset of rain and represented as:

$$LP = O_{date} - d \tag{3.24}$$

Where LP is land preparation date, $O_{date}$is onset date, d is a parameter indicating a date before the onset date.

Households that anticipate early onset of rain will prepare their farmland earlier than those households who anticipate onset at the normal time or late. After land preparation, households search for the best time to plant their crop. Perfect timing of planting dates is one of the key factors that strongly affects crop production in rain-fed agriculture [13, 96, 129]. This is especially true when the rainy season starts with some light showers followed by dry spells, which can cause poor crop emergence or desiccate a young crop [96]. Planting requires sufficient amount of moisture in oder to crops to germinate [130].

The time of planting date is also affected by household expectation of onset similar to land preparation date. Since households' expectation of onset date is different, the ideal time for planting date varies from household to household. Ati et al. [13] suggested that the ideal planting date is a date after onset with at least with amount of moisture equivalent to minimum effective rain (MER). The planting date can be defined as:

$$PD = O_{date} + \delta \tag{3.25}$$

Where PD is planting date, O_{date} is onset date, and δ is the first date after onset date with a rainfall amount at least equivalent to MER.

The next farming activity is weeding. Although weeding time and frequency depend on the type of crop, we highly simplify the determination of weeding date and frequency. In the current status of the model, we only assume one weeding date for each crop type. Househol choose a date that falls between three to five weeks after planting date and weed their crops. The weeding will enhance the growth of the crops by a small margin.

The final farming activity is harvesting. Appropriate harvesting time is essential in order to get maximum yield. Crops are ready for harvest when they are matured and reach to the late stage of their growing period. Crops that are harvested early provides low yields and poor quality due to immaturity and high moisture. Late harvesting also results in shattering of grains and affects the yield. Households can harvest their crop anytime when the crop reaches its length of growing period (LGP) as:

$$HD = PD + \tau \tag{3.26}$$

Where HD is harvesting date, PD is planting date, and τ is a date the household decide to harvest, which is either before or after the LGP of a given crop. The decision of harvesting date, therefore, entirely depends on the urgency of the household to collect their harvest. At the harvesting time, the household calculates the farm income based on yield of a given crop as:

$$Inc = Y * P \tag{3.27}$$

Where Inc is crop income, Y is crop yield at the harvest time, and P is price of crop. If the household plants more than one crop, the total farm income will be calculated as:

$$Inc_F = \sum_{c-1}^{n} Inc_c \tag{3.28}$$

Where Inc_F is total farm income and Inc_c is income of crop c.

Herding

Herders' movements, including migration pattern, are more complex and highly influenced by individual decision-making and the relative importance of ecological, cultural, political and economic factors [35, 51, 110]. These factors can affect the movement on different scales of precision. Ecological factors determine the general features of the migration patterns (such as seasonal migrations from one ecological zone to another), while non-ecological factors determine the concrete details of movements and schedules. The relative importance of each factor depends on the context of the study areas. Dwyer and Istomin [50] suggested existent complex human–animal relations should be considered in order to understand the herders' decisions with respect to movement.

We consider herders' movement as an adaptive mechanism influenced by household perception, and ecological and socio-economic factors. Ecological factors affect movement through their influence on animal behavior, whereas non-ecological factors do so by influencing the herders' actions. Households decide where to move in order to increase productivity and minimize hazards mainly by looking after herds, searching for more suitable pasture in the surrounding area, moving herds to higher quality pasture in far places, and splitting of herds in case of bad climatic conditions such as drought. To accomplish their objective, herders need to search for the best grazing area and move their herds toward it by using their knowledge and experience. Herders decide the best place to move their herds by considering the vegetation level, its distance from their campsite, and distance from future target area or vision parcel. The best parcel is selected using:

$$Parcel_{best} = max \prod^{n} Veg\left(aDist_{camp} + \Omega\right) + cDist_{vision} \tag{3.29}$$

Where a, b are parameters indicating the influence of distance to camp and vision parcel respectively. The parameter, Ω, controls the need to return back to camp. Vision parcel location changes over time. The value of "distance to camps" is influenced by the vegetation level of the parcel under consideration. When the parcel has high vegetation level, herders keep their distance near to their camp site. However, in case of minimum vegetation coverage or dry season, herders give more weight towards the vision parcel. How fast the herder can travel depends on the number of parcels he can compare in each steps, which is directly related to the adaptive capacity of the herder. The parameter n is larger if the household is adaptive. Adaptive households possess better understanding and information about their surrounding environment than do maladaptive households. Maladaptive households haave limited vision and information about their surrounding areas. They can only observe the vegetation within the distance they can move in a day. However, adaptive agents have adequate information about the vegetation condition of further locations and adjust their travel distance by comparing the vegetation in the surrounding area with the vegetation in the other areas. This simplification is not far from reality. For instance, McCabe [111] found out that herders with better capacity travel longer distance in time of drought than those households who do not have sufficient resources.

Each household that has herds calculates the income the household can get from their herding. Income can be in the form of dairy product or meat. The dairy product is calculated daily. It is highly influenced by the biomass of the herd. Well-fed herds produce more dairy products than hungry herds. The dairy income is calculated as follows:

$$Inc_{diary} = p * TLU * \frac{h}{k} \tag{3.30}$$

Where Inc_{dairy} is dairy income, TLU is total herd size, p is diary price, h is herd biomass, and k is maximum herd biomass.

Other herding income comes from selling herds, which is calculated as:

$$Inc_{meat} = q * S_{TLU} \tag{3.31}$$

Where Inc_{meat} is herd-sell income, S_{TLU} is number of herds a herder sells, and q is the unit price of a herd. The total income from herding is the sum of dairy income and herd sale and can be represented as:

$$Inc_H = Inc_{dairy} + Inc_{meat} \tag{3.32}$$

Off-farming

Off-farm income depends on the amount of labor committed for off-farm activity and the probability of income return to households. The revenue of off-farm activity is given by:

$$Inc_L = \sum \alpha L * s \tag{3.33}$$

Where $Inc_L$is income from off-farm activity, s is a parameter indicating daily labor wage, and L is a family member engaged in off-farm activity, and α is a parameter indicating the proportion of income return to family.

It is essential to mention that in most of sub-Saharan Africa, including South Omo, the availability of off-farm activity is very limited. The most common way of getting addition labor is through labor sharing or with close family members or neighbors, which does not directly contribute off-farm income. However, any change in labor size in a household due to movement might have implication for the consumption level of the household. Households whose members are moving to relatives or neighbors for work for extended periods will have less consumption expense proportionate to the number of members who are engaged in labor exchange. However, such labor movement may damage the marginal revenue that household may get from labor in either farming or herding, or both activities. A household that gets additional labor may have extra consumption expense but may have extra advantage on the labor allocation for herding or farming activities. If the model runs with enterprises, the off-farm income values will have direct implications on the total household revenue. This is mainly due to the assumption that the expansion of large-scale land acquisition and the introduction of different enterprises may create an additional opportunity for households to engage in off-farm activities with attractive salary and influence the household to consider such livelihood options as discussed in section 2.3.2. For simiplicity, the search for labor-related works is assumed based on proximity of opportunity.

Household Labor Allocation

Each household covers its labor requirement by its own members. The allocation of labor in a given period depends on different socioeconomic and environmental factors that have direct impact on a household's decision-making, such as amount of farmland for crop production, number of livestock, family size, climatic condition, amount of available labor, household's wealth status, and off-farm opportunities in the region. A household determines the proportion of labor to be allocated for a given livelihood option by comparing the expected return of each livelihood option (herding, farming or off-farming activities) and allocates the highest proportion of labor to whichever alternative yields the highest expected return and the lowest proportion to activity with the lowest expected return.

Household Consumption and Change in Wealth

Household production activities are intended to cover nutritional requirements. In Ethiopia, it has been indicated that household consumption accounted for a significant proportion of households' total expenditure in rural areas [124]. It accounted for, on average, 60% in 1995/96 and 67% in 1999/2000 [117]. Although there might be different types of household expenses, in the model households emphasis only to meet their nutritional requirements in each time step. To do so, households accumulate wealth that emanates from all livelihood options and meet the minimum nutritional requirements in order to subsist. The total consumption requirement of the household to meet nutritional needs is given by:

$$C_H = \Lambda H_{size} \tag{3.34}$$

Where C_H is consumption of the household, Λ is a parameter indicating daily per capita consumption requirement, H_{size} is the total number of members in the household. In addition to consumption expenses, households may have other expenses that are directly related to the livelihood activities. These expenses are occasional and demand-based. For instance, households engaged in farming that would like to apply adaptation options may have to spend some expense to cover farm input costs such as fertilizer cost, high-yield seed cost, or new farmland cost. Similarly, households engaged in herding that would like to restock their herd size as part of adaptation option will have an additional expenses in addition to consumption expenses. Including these additional expenses in the consumption expenses of the household, the total expense of the household will be:

$$E_H = C_H + OE \tag{3.35}$$

Where E_H is the total household expense, and OE is all other expenses of the household.

The net wealth of the household at each time will be calculated as:

$$W_H = R_H - E_H \tag{3.36}$$

Where W_H is the net wealth at the end of the period, R_H is the total revenue of the household, and E_H is the total expense of the household. The total revenue of the household is mainly generated from all the livelihood options in which the household has engaged. Hence the total revenue of the household is expressed as follow:

$$R_H = Inc_F + Inc_H + Inc_L \tag{3.37}$$

A household needs to have positive wealth to subsist. If the household moves to negative wealth, the household will be forced to migrate or exit from the system.

Climate Change Experience and Learning

Learning is one of the characteristics of households. Humans learn either by imitating, from past experiences, or from instructors [91]. It is indicated that in a rural context, rural households exhibit similar learning patterns to respond to the climate variability [57, 94]. In a situation where provision of training and farm extension activities are limited, rural households usually acquire knowledge about the impact of climate change from their experience and by imitating their neighbors. A similar notion is implemented to model the learning behavior of rural households in the model. If the household is willing to apply adaptation measures, the household will tend to learn more from neighbors that have more experience than the household. A household's adaptation experience is expressed as follow:

$$ADP_t = ADP_{t-1} + \gamma \left(\phi + \partial \frac{\sum HH_{ADP}}{TotalHH} \right) + \varepsilon \tag{3.38}$$

Where ADP_t adaptation experience of a household at time t , ADP_{t-1} is previous adaptation experience of household, γ is a parameter indicating learning rate, ϕ is ingenuity level of the household, ∂ is a dummy variable (0 if the household is a maladaptive agent; otherwise, it has a value of 1), and HH_{ADP}, is number of adaptive household in the neighborhood.

Update Memory

Rural households predict future rainfall pattern based on their previous experience and traditional knowledge. Luseno et al. [103] indicate that most pastoral societies in the Southern Ethiopia and northern Kenya utiliz indigenous climate forecasting methods. Pastoralist households form prior beliefs about the upcoming season's climate based on past experiences and indigenous climate forecasts. These beliefs are then subject to revision following reception of new forecast information from external sources. Pastoralists act on their posterior beliefs as to seasonal climate patterns. Slegers [146] also found out that previous drought experiences shape an individual's memory and are an important influence on how someone defines drought in Goima, Tanzania.

We incorporate the influence of prior knowledge on the prediction ability of rural household in OMOLAND model by allowing the rural household to remember the previous years rainfall patterns. Households remember their previous actions in order to make future decisions. Household stores multiple years of information related with climate change such as onset date, and amount of rainfall. Household make prediction of climate indices at the start of the rainy season based on previous years climate indices as discussed above. Their predictions, however, may or may not be accurate.

At the end of the season, households compare their predictions of climate indices with the observed climate situation of the season and make appropriate change to their memory. In the model, as we assume household agents as myopic and bounded rational. We assume that not all household accurately remember the observed climate situation of the season correctly as we assume that households are bound rational as discussed in section 3.6.1.2. Some of the households stick with their prediction even if their prediction contradicts thier observation . As households update their memory, they discard old information because their memory space is limited. Figure 12 shows the update procedure of household memory.

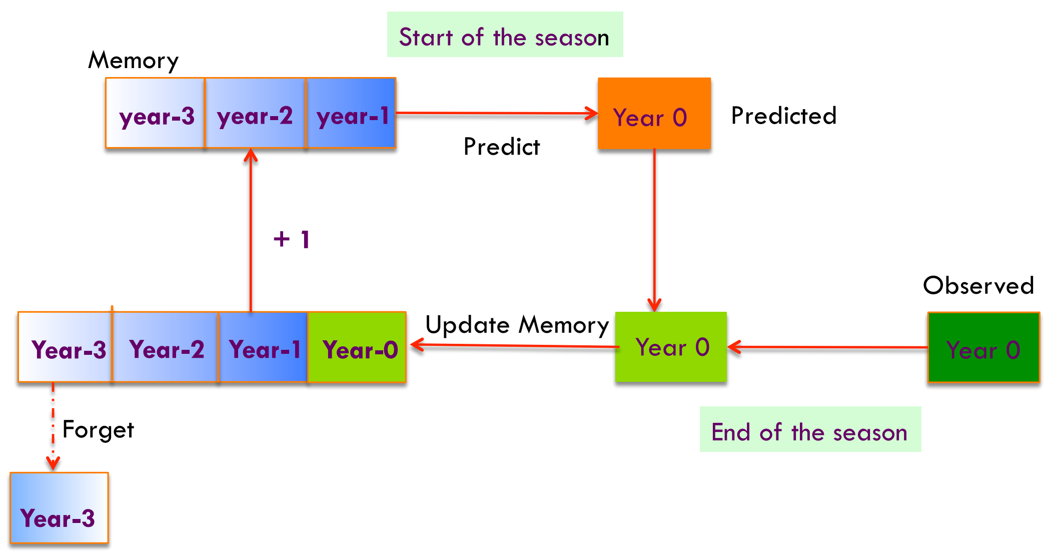


Figure 12: Household's memory update sequence

3.6.3.3.4 Crop Submodel

Crop submodel focuses on crop growth and yield determination. Crop growth depends on soil, water, air, and sunlight [8]. Although all these factors are prominent for crop growth, we analyze crop growth only using crop water requirement and soil quality (soil fertility).

Crop growth at a given parcel at a given time is given as:

$$G_t = G_{t-1} + G_{gt} \tag{3.39}$$

Where G_t is the crop stage at time t , G_{t-1} is the crop stage at time $t-1$, and G_{gt} is daily growth level, which is a function of soil quality and moisture and calculated as:

$$G_{gt} = \omega q m \tag{3.40}$$

Where ω is the growth rate parameter, q is soil quality of the land[**?**], and m is a moisture index. The value of G ranges between 0 and 1, in which 0 indicates that crop has not yet germinated or die while 1 indicates that crop is matured and ready for harvest. The soil quality of a given parcel is derived from soil data and slope. The soil quality of a given parcel can be enhanced if the household is using fertilizer. In case of fertilizer usage, the fertility of the soil will reach the maximum soil quality level.

Crops are sensitive to water variability and the moisture index dictates daily crop growth [8]. Crops that get sufficient moisture throughout their growing period will grow normaly and provide the highest yield. Excess moisture or stress will affect crop growth and yield. The moisture index m is determined based on the gap between the parcel moisture (rainfall), and the optimal crop water requirement. The moisture index m is given as:

$$m = 1 - \left(\frac{r - ET_c}{ET_c}\right)^2 \tag{3.41}$$

Where r is daily rainfall or parcel moisture, and ET_c is crop evapotranspiration, which is optimal water requirement of a given crop, and m is moisture index. The amount of water required for optimal crop growth varies depending on the type of crops and growth stage. To determine the water requirement for optimal growth of a given crop, we applied FAO water requirement equation [8]. According to Allen et al. [8], water requirement of a crop at a given growth stage is determined based on crop evapotranspiration and crop factor. The crop water requirement equation is given by Allen et al. [8]. as:

$$ET_c = k_c * ET_o \tag{3.42}$$

Where, ET_c is crop evapotranspiration or crop water need (mm/day), k_c is crop factor, and ET_O is reference evapotranspiration (mm/day).

Table 5: Crop water requirement (Source: [8, 12])

Crop	Moisture (mm)	Stage							
		Initial		Development		Mid-season		Late	
		Days	Kc	Days	Kc	Days	Kc	Days	Kc
Maize	500-800	30	0.4	50	0.8	60	1.15	40	0.7
Sorghum	450-650	20	0.35	30	0.75	40	1.1	30	0.6
Wheat	450-650	15	0.35	25	0.75	50	1.15	30	0.45
Teff	750 -900	15	0.8	20	1.2	30	1	20	0.5

As shown in Table 5, k_c value varies with crop type, growth stage, and length of growing period. To determine the daily crop water requirement, we approximate the daily k_c value for each crop using a polynomial function for each crop type. Although this might be a very simplistic assumption, it keeps the k_c value along the growing period as it is given in Table 5 and increases the robustness of crop growth routine under different climatic conditions. The ET_o depends on the mean temperature value, which is relatively constant in the study area. We use 9 millimeters, which is equivalent to the average estimated value of arid and semi-arid regions in East Africa [8]. Based on these modifications, we develop a crop water requirement equation for each crop and determine the daily ideal (actual) water requirement of each crop. The k_c for each day is estimated using a polynomial function as:

$$k_c = aT_c^2 + bT_c + c \tag{3.43}$$

Where k_c is a crop factor, T_c is a date after planting date (planting date is considered as date 0), and a, b are coefficients for T, and c is the constant term. Due to k_c value on each development stage, the level of water requirement of each crop type increases until it reaches to its development stage and decreases as it reaches to maturity or late season stage.

In the model, two water sources are included: from rainfall, which is the main source of moisture in the study area, or from rivers through irrigation. In case of irrigation, the moisture index is kept as constant ($m = 1$) as there is sufficient water equivalent to the ideal water requirement of the crop throughout the growth period.

Crop yield is determined based on the crop growth rate, its length of growing period, and crop management. It is calculated as:

$$Y = G_t Q \kappa A L \tag{3.44}$$

Where G_t is the growth level at time t, Q is a parameter indicating the maximum crop yield per hectare, κ is the harvesting date factor, which indicates the gap between the ideal harvesting date and current harvesting date, L is labor factor, A is area of the land per hectare. A crop reaching to harvesting period (or near its maximum length of growing period) provides the maximum yield. The harvesting date factor depends on the household agent decision when to harvest. If the household decides to harvest the crop earlier or later than the ideal crop harvesting date, which is the length of growing period of the crop, the harvesting date factor changes accordingly based on the following equation:

$$\kappa = \begin{cases} 1 & if \ |LGP - HD| \leqq d \\ \\ 0, & otherwise \end{cases} \tag{3.45}$$

Where κ the harvesting date factor, d is a paramter indicating ideal harvesting time before or after crop LGP, HD is the current harvesting date, and LGP is the ideal length of growing period of the crop.

3.6.3.3.5 Herd Submodel

Livestock is modeled as single herd unit and is measured with TLU. In the model, livestock reproduce or die depending on the household management capacity and availability of forage, which in turn depends on weather, soil quality and the number of livestock consuming the forage at a given time. The livestock size at a given time is given by:

$$H_t = H_{t-1} + H_{gt} \tag{3.46}$$

$$H_g = \beta \nu H \tag{3.47}$$

$$\nu = 1 - \left(\frac{0.12}{0.12 + \left(\frac{Bioass_{herd}}{BioMass_{max}} * l \right)^3} \right) \tag{3.48}$$

$$l = \alpha \left(\frac{\frac{H_{t-1}}{(L*\lambda)}}{\left(1 + \frac{H_{t-1}}{(L*\lambda)^2} \right)} \right) \tag{3.49}$$

Where H_t is herd size at time t, H_{t-1} is herd size at time $t-1$, H_{gt} is herd growth at time t, l is management index indicating the manaagement skill or capacity of the household, β is a parameter indicating herd growth rate, ν is herd biomass index, α is the adaptive capacity of the household, λ is a parameter indicating the maximum number of herd a herder can manage, L is amount of labor allocated by the household. The climatic variation affects the rate of livestock reproduction as it affects the herd biomass level, which indicates that in good weather condition livestock reproduce more often than in bad weather conditions [109, 126, 152].

3.6.3.3.6 Enterprise Submodel

The representation of enterprise is designed mainly to capture two of the major influences of enterprises on the rural systems as discussed in section 2.3.2. First, enterprise agents influence the biophysical environment by occupying a large tract of land and changing the land property from grazingland to farmland as they utilize it for production of different commercial crops through mechanized farming system. The occupation and conversion of land will have direct implication on the amount of vegetation production in the system. Conversion to grazing land to commercial farming reduces the total grazing area. This in turn will have implication for livestock production, as the livestock production in the zone solely depends on grazing. Moreover, occupation of land may also affect the movement of herds from place to place by fragmenting the grazing areas. Second, enterprise affects the system by introducing a new livelihood option to rural households. Enterprises create labor market in which rural household can participate. Such opportunity may enhance households' income diversification options. Hence our model is designed in a way to accommodate these two concepts.

Enterprises are introduced at the start of the simulation and increase in number over time. The growth rate of enterprises is determined by the assigned enterprise growth parameter. Hence the growth of enterprises in the system is given as:

$$E_t = E_{t-1}(1 + \aleph) \tag{3.50}$$

Where E_t is the total number of enterprises at time t, E_{t-1} is the total number of enterprise at $t-1$, and $\aleph$ is a parameter indicating the growth rate of entrprise. The amount of land a given enteprise owns is assigned randomly between the minimum and maximum parameter value. Each enterprise also is assigned a maximum labor capacity based on the amount of land it possesses.

The enterprise determines the need for labor and announces the openings to the public. The positions will stay open to the public until filled. When the positions are filled, they are no longer searchable by the public and the enterprise does not take on any more labor. Each position is temporally. When the task reach its time limit, the enterprise dismisses all the employees and determines when to start a new task.

It is essential to point out that it is not entirely the enterprises that have the power to dismiss worker. Workers can have the power to resign from working in the enterprise. Since in most rural systems, off-farm activity is subsidiary to farming and herding, the household may abandon the off-farm activity at any given time and decide to return to agricultural activities [67]. If a household member decides to leave his off-farm position, the enterprise will assess the need for additional labor and announce the position to the public immediately [140].

In our model, each enterprise pays workers each day with an equal amount as indicated in the parameter. Skill or experience of workers is not considered in the model. Although these factors may have implications for the amount of money a worker can generate, we believe that in the context of South Omo where off-farm activity is in its early stages and the main opportunity is related to short-term labor activities, this notion has not matured enough to influence the outcome of the model.

3.6.3.3.7 Institutution Submodel

Although insitutions play a siginificant role in the rural systems, the representation of institutions in the model is very simple as this disseration focuses primarily on the rural household decision-making processes, their adaptation mechanism and their interaction with the boiphysical environment and enterprises. We utlized a simplified version of RebeLand [33] representation of institution to test different policy scenarios.

There is only a single institution in the model, which has a scope that covers the whole study area. The institution carried out two main tasks: capacity building and relief support to rural households. Depending on the parameter values, an institution agent selects households randomly and provides climate change adaptation training. The training changes the adaptation experience level of the households. Moreover, the institution also provides relief support to selected poor households. Both types of support are given once in a month.

3.7 Model Verification and Validation

Although agent-based modeling provides substantial advantages for modeling complex coupled human and natural systems, there are still caveats on the progress of model verification and validation [9, 38]. Indeed, Ormerod and Rosewell [131] pointed out that currently there are no formal or standard means of verifying and validating agent-based models. It is usually difficult to develop a simple mathematical formula for model verification and validation from a single run due to the stochasticity and interaction of model components [15]. Similarly, Balci [16] also suggested that models that utlize object oriented paradigm often are difficult to assess their accuracy dut to the dynamic nature and diverse patterns of interactions among model components.

As the OMOLAND model incorporates different components, it is important to point out that the verification and validation of the model need further experiments and comparison of the outcome of the model with longitudinal socioeconomic data, which is currently unavailable for the study area. Given the limitation on data and the complexity of issues raised in this study, we have conducted the following verification and validation of the model.

3.7.1 Model Verification

Verification is a process to testing the accuracy of the logic of the model through its computer programing to ensure that the model is built as intended by the conceptual model [16, 38]. We implement the following verification procedures to verify the OMOLAND model: code walkthrough, profiling, and parameter sweeps.

Code walkthrough

We have performed code walkthrough by reading the codes line by line to ensure the codes are written in a logical and accurate way from the inception of the model till the final stage of the model. We have checked the accuracy of mathematical representations, method calling, parameter settings, naming standards, commenting, and statistical outputs.

Model Profiling

Another verification profile that we have applied was model profiling. Model profiling is performed to assess the consistency, performance, and the speed of the model by examining the frequency of key code elements (parameters, operations, or methods) used in the model. We performed model profiling using the NetBeans profiler. We examine the output of model profiler and made necessary changes to ensure the model performance is enhanced.

Parameter Sweeps

We also perform model verification through parameter sweeps to test the behavior of the model. We particularly have focused on monitoring the model outcomes with different extreme climate event values. For instance, we monitor the livestock number, as livestock are sensitive to rainfall variability. Figure 13 and Figure 14 show the ANOVA analysis of livestock number and total population, respectively, in run with three frequency levels (5, 10, and 15 years) and three intensity levels (50%,70%, and 90%). The p-value (0.000001) suggests that there is significant variation between each of drought event. The box plot shows that in all drought intensity levels, the livestock number with drought frequency level of 15 years is greater than the other two frequency levels. Although the model is sensitive to climate variability, it shows that even in the harshest extreme event there are still livestock that manages to survive as shown in Figure 13. As we observe the sensitivity of the population number to climate variability, the model result indicates that there is still significant variation along the climate scenarios as shown in Figure 14.

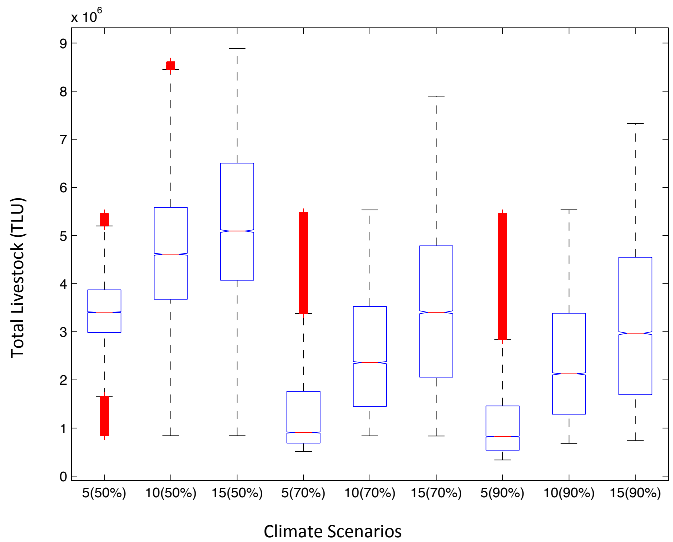


Figure 13: Anova analysis of livestock with various climate scenarios 5, 10, and 15 indicate frequency of drought episods and 50%, 70%, and 90% indicate intesity of drought

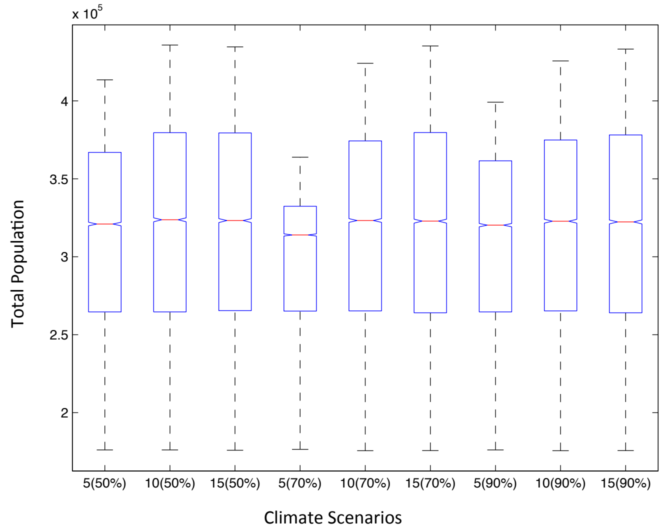


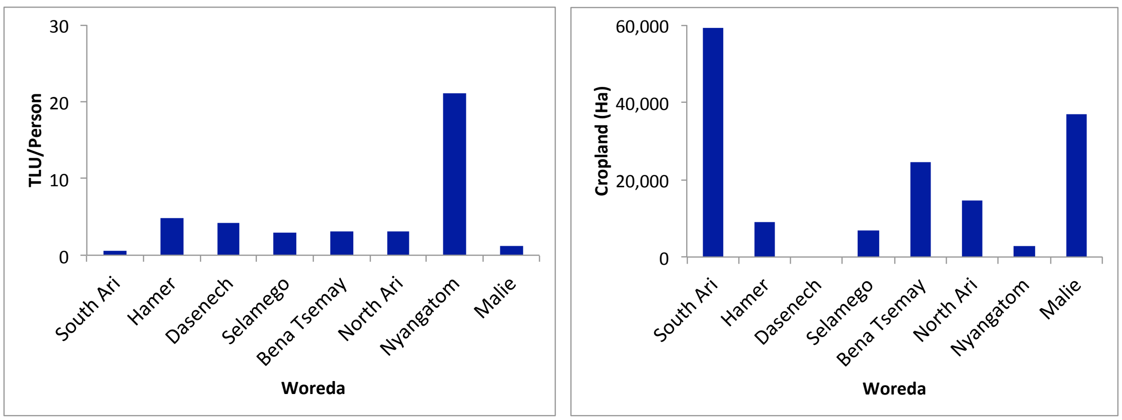
Figure 14: Anova analysis of population with various climate scenarios 5, 10, and 15 indicate frequency of drought episods and 50%, 70%, and 90% indicate intesity of drought

3.7.2 Model Validation

Model validation is a process to check whether the results from simulation model runs matches with empirical data. It involves ensuring the goodness of fit of the model to data[9, 38]. We have conducted model validation using empirical data, and filed visit.

Validation with Emprical Data

Although there is no time-series statistical data of the zone, we have performed empirical validation by comparing the overall pattern of the model results with empirical data of year 2011 developed by the zonal finance and economy development bureau. Figure 15 shows livestock numbers and areas covered by crops in each woreda in 2011. Based on the 2011 data, Nyangatom woreda has the highest livestock per capita level while South Ari has the least livestock per capital level as shown in Figure 15a. When we compare areas covered by crop in 2011, South Ari shows the highest number of croplands followed by Malie woreda while Dasenech woreda shows the least number of croplands followed by Nyangatom as shown in Figure 15b.



(a) (b)

Figure 15: Livestock and crop production by woreda based on emprical data of 2011 a) number of livestock (TLU) per person per woreda, b) croplands(hectares) per woreda

Figure 16 shows livestock per capital level and croplands of each woreda from model run of 50 years. The model run was conducted with erratic rainfall patter and with default parameter values with no enterprise or institution representation. The median for 50 years run of each woreda is indicated by the red centerline, and the first and third quartiles are the edges of the blue area (inter-quartile range). The extreme values are the ends of the lines extending from the inter-quartile range. As we compare the livetock per capita level of the model run, as shown in Figure 16 a, to empirical data, as showin in Figure 15aa, the model captures the overall livestock distribution of empirical data. Similar observation can also be seen in the crop production. In both the model and empirical data as shown in Figure 15, crop production is dominant in the northern part of the zone where there is sufficient moisture, while livestock production is dominated in the southern part of the zone where rainfall is relatively low, which is similar to the discussion in section 2.2.

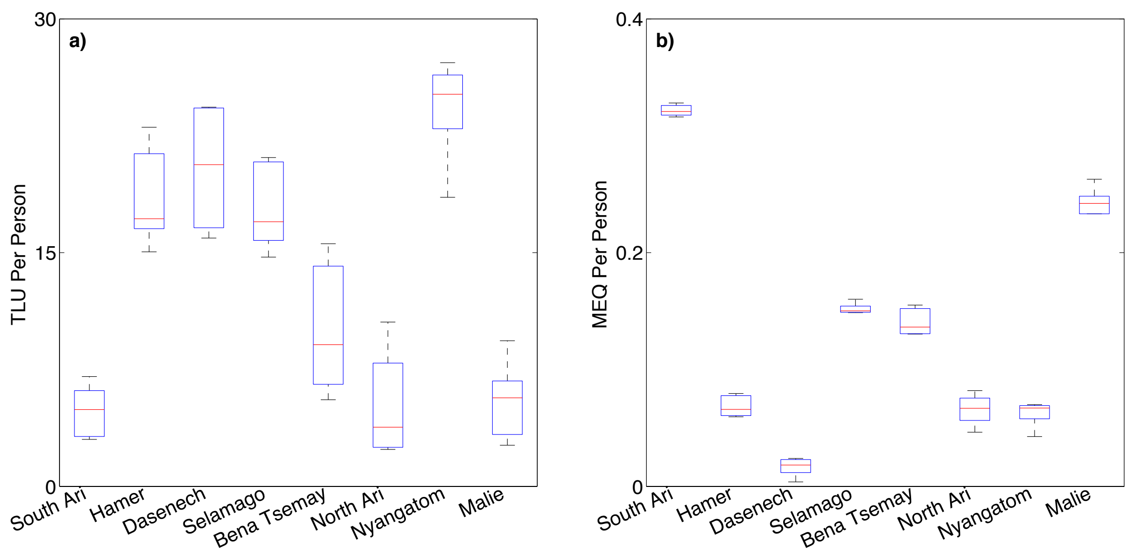


Figure 16: Livestock and crop production by woreda with “erratic rain” a) number of livestock (TLU) per person per woreda, b) crop (Maize Equivalent -MEQ in kilogram) per person per woreda

Validation with Field Visit

We also validate the model using data that we collected while we conducted a reconnaissance field survey from January 2, 2013 to January 10, 2013 in all woredas of the South Omo zone except Nyangatom and Selamago due to security concerns through a National Science Foundation (NSF) Dissertation Improvement Grant. The main aim of the field visit was to observe the landuse pattern, types of agriculture systems experienced in each woreda, the status of current large-scale and acquisition in the zone. The farming practice in the South Omo zone varies not only across woredas but also within each woreda. For instance, in Bene Tsemay woreda, in area where there is higher rainfall, there are relatively conspicuous farming lands. Another striking finding from field visit was the variation of crop planting patterns among neighborhoods. Although the field visit was made in January, which is commonly dry month, we have observed that there were various kinds of crops on the fields with different growing stages. Some crops were already harvested (bare croplands); some of them were in their harvesting stage (e.g dry maize or sorghum stands), while others were in their early growing stage.

To validate our model results with our filed observation, we count the total number of times (frequency of) a given farmland has covered with crops within the 50 years of the model run. The result is shown in Figure 17. Our assumption is that if our model behaves well, the model result should indicate that there is variation between neighborhood croplands. As shown in Figure 17, our model captures similar behavior across the zone. It indicates that the total number of farming varies among neighborhoods although households share relatively similar biophysical and climate conditions.

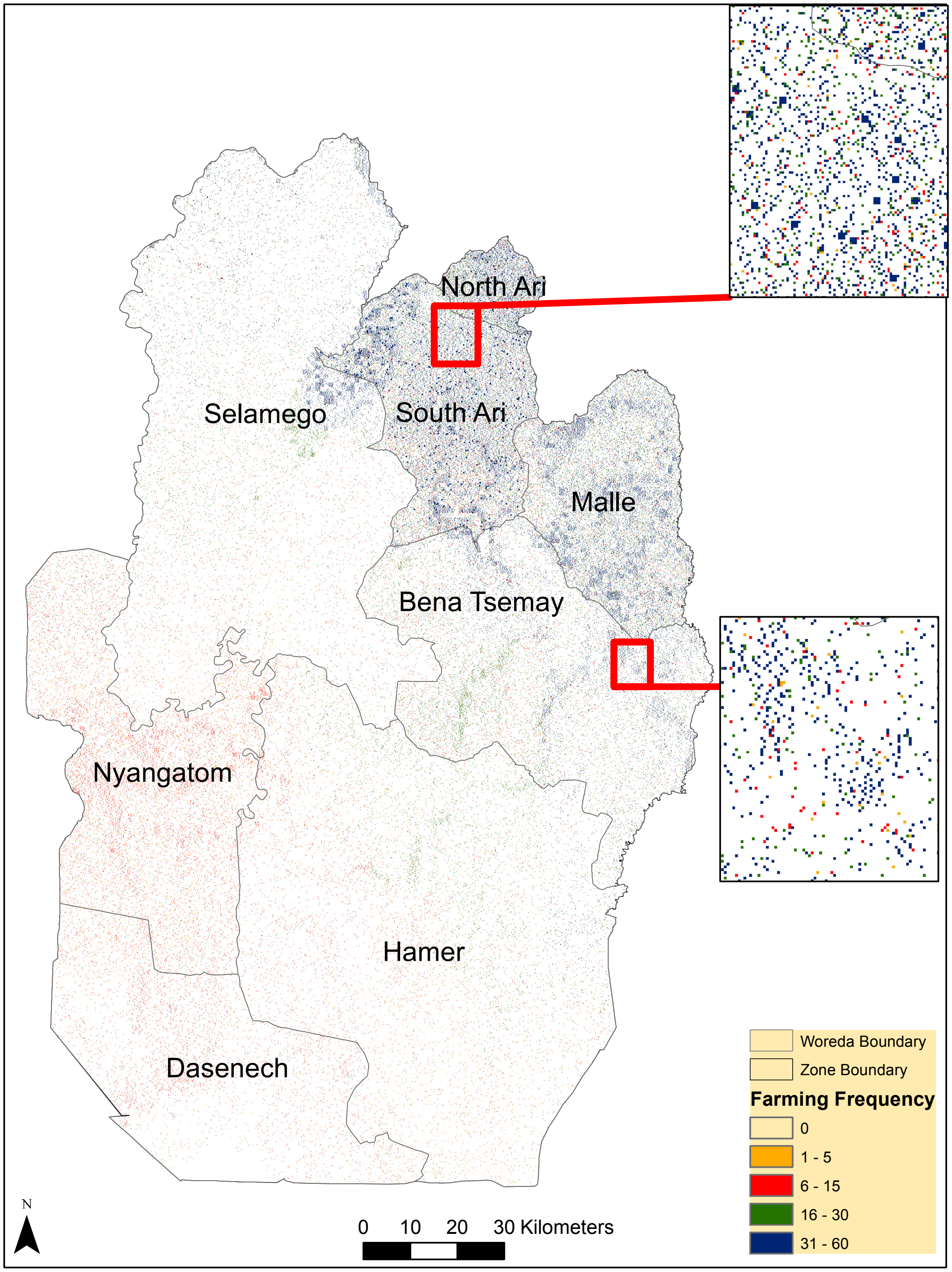


Figure 17: Frequency of crop planted per hectare
The two boxes at the right show variation in frequency of crop planted per hectare around neighbohoods

In general, the results from model verification and validation indicate that the OMOLAND model behavior resemble to empirical data. These results are very encouraging and have given us confident to perform experimental scenarios.

4 COMPUTATIONAL SIMULATION RESULTS

4.1 Introduction

In this chapter, we present the results of our model for the three main research themes. Each theme relates with the main research question of this dissertation. Each theme has three sections: experimental scenario, results and discussion. For each theme, we first present the model setting for each experimental scenario, and present results of each scenario followed by discussion. We finally present a conclusion for the chapter.

4.2 Theme 1: What are the Impacts of Climate Change on Rural Households?

The main aim of this experiment is to explore the impact of climate change on rural households and how the households' perception of climate change affects their adaptive responses. The model components will focus on only household-climate-environment interactions.

4.2.1 Experimental Scenarios

We perform a set of experiments in order to examine some of the characteristics of OMOLAND systems that are particularly relevant to the impact of climate change on rural households. We particularly focus our analysis on understanding how climate change affects the adaptive capacity of rural households, and how rural households mange to survive under climatic extreme events. We look into the following three experiments: (a) a base scenario based on “normal” climate situation (b) the effect of rare extreme events on rural households, (c) the effect of consecutive extreme events on rural households, (d) the effect of erratic climatic extreme events, which resembles the real rainfall pattern of the study area.

We begin the modeling processes by creating a mean annual rainfall with normal onset and amount for the entire region. We generate the mean annual rainfall by calculating the mean of 109 years (1901 to 2009) of monthly rainfall. We assume that this mean annual rainfall is an indicator of the normal (or “good-year”) climatic condition of the region and consider it as a baseline scenario state. We run the simulation by keeping this mean annual rainfall year to year, which indicates that the climate condition of the region is normal. The normal climatic situation will help us to understand how rural households interact with the environment and how their characteristics and livelihood decision-making affect their probability of survival (or their success). We try to explore the carrying capacity of the environment to sustain the livestock and human population under a normal climatic situation.

In the second experiment, we introduce drought as an extreme event. We introduce drought every 5, 10, and 15 years with a severity level of 50%, 70%, and 90% changes from the mean. In each extreme event year, we decrease the rainfall amount by the assigned severity level from the mean annual rainfall while keeping the other years normal. The change in climate situation, particularly the occurrence of extreme events now affects the growth of crops and grasses, and ultimately affects rural households by enhancing or disrupting their production systems. We explore the resilience of rural households to these events and their capacity respond to the severity of climatic events. By doing this, we look at the implication of climatic extreme events on the adaptive capacity of rural households.

In the third experiment, we increase the frequency of extreme events by allowing consecutive occurrences. We keep the same time interval of occurrence of events as in the second experiment but introduce additional drought events to occur in two consecutive years. Our aim is to explore the implication of consecutive occurrence of extreme events. We explore how the household resource base be altered by the extreme events and to what level the household copes with long term extreme events.

Finally, we explore the rural household resilience to erratic climatic conditions. The rainfall pattern of the zone is erratic and incorporates both good and bad years. It shows high variation not only year to year but also month to month. We utilize actual rainfall patterns of the zone for this experiment. We utilize 50 years of rainfall data from 1949 to 2009. We choose 50 years mainly because it is the plausible range used in most agent-based landuse and land cover change models [57, 136].

In each experiment, the main agents consider are the rural households residing in the South Omo zone; therefore, there are no enterprises or institutions in this model setting. The simulation runs for 18,250 iterations (each iteration step is a day and 18,250 iterations are about 50 years). In each experiment, we keep the first 3 years to have a normal climatic condition so that the model initialization stabilizes. We then introduce all the climatic events so that all the variation will directly associate to the variation in the climatic events. Additionally, to observe the sensitivity of the model, we run a set of 30 simulations with a constant initial parameter setting, which is the default value of the parameters. Differences between individual simulation runs can be attributed to the stochastic elements of the model.

4.2.2 Results

The South Omo zone has exhibited various climatic shocks in the past. The resilience of the rural households and the environment is threatened by the intensity and frequency of the climatic shocks. The model simulation focuses on exploring the effect of changes in climate indices on rural households in the South Omo zone and how they cope with different climatic shocks. As the rainfall directly affects the environment, particularly vegetation growth and crop production, the possibility of sustaining large human and livestock population varies with climate variation.

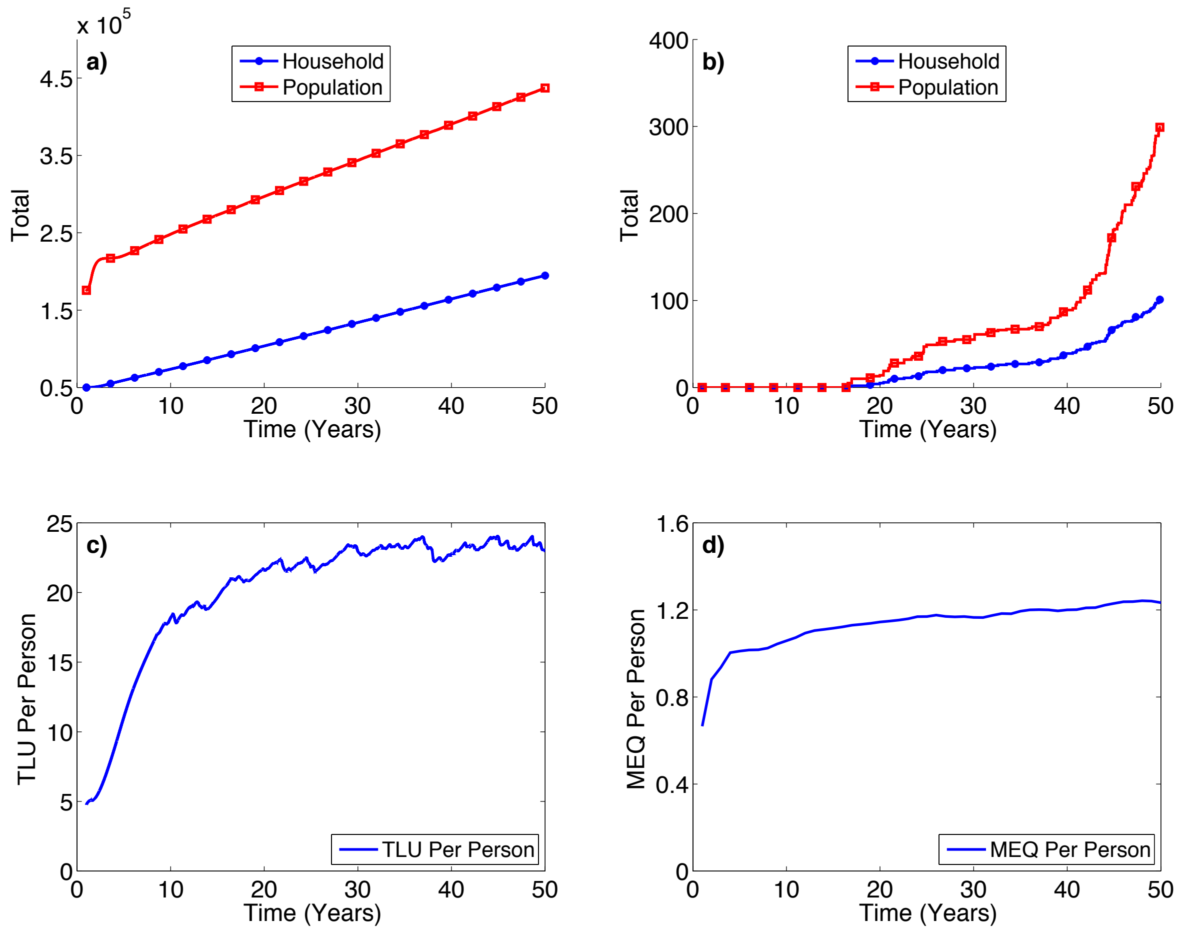


Figure 18: Household dynamics with "good year" scenario
a) household and population number over time , b) number of people migrating from the system, c) number of livestock (TLU) per person, d) crop (MEQ) in kilogram per person. (Note: MEQ (Maize equivalent) used to aggregate all crop types in to a single unit by convering the price of each crop to maize, e.g., 1KG of wheat = 1.67 MEQ; 1KG of teff = 2.5 MEQ, 1KG of sorghum = 0.8 MEQ)

Under "good year" scenario, household numbers increase over time and reach to 155,916 after 50 years as shown in Figure 18a. The total population increases by 47% over the simulation period and the population density changes from 0.03 to 0.16 people per sq. kilometers The good climatic condition throughout simulation favors both livestock and crop production. As shown in Figure 18c, per capita livestock numbers increases sharply in the first 10 year and start stabilizing as they reach ecological capacity. The trend in crop production also shows an ascending trend but not as significantly as livestock as indicated in Figure 18d. The overall success of households under this climatic scenario can be seen by monitoring the rate of migration over the simulation period. Figure 18b indicates the number of households and population migrate from the system due to loss of wealth. Although population density increases over time, households seem favored by the climatic condition and all but a few are able to sustain their livelihood.

Figure 19 shows the proportion of herding and farming productivity in each woreda. In Selamago, Dasenech, Nyangatom, and Hamer woredas, the number of livestock per person shows a growth trend throughout the simulation, while in South Ari and North Ari, the number of livestock per person decreases slightly as shown in Figure 19a. As shown in Figure 19b, in all woreda, crop production increase over time with different rates expect Dasenech, where the number of people engage in crop production is near to zero. The characteristics of each woreda are striking as we compare their productivity between livestock and crop production. Except Selamago and Bena Tsemay, which have high productive on both livestock and crop, the other woredas exhibit the opposite trend of productivity on livestock and crop. For instance, South Ari, North Ari and Malie accounts the lowest TLU per person but produce the highest proportion of MEQ per person as compared to the other woredas. In contrary, Nyngatom, Hamer, and Dasenech, which have the highest TLU per person, account for the least MEQ per person as compared to other woredas.

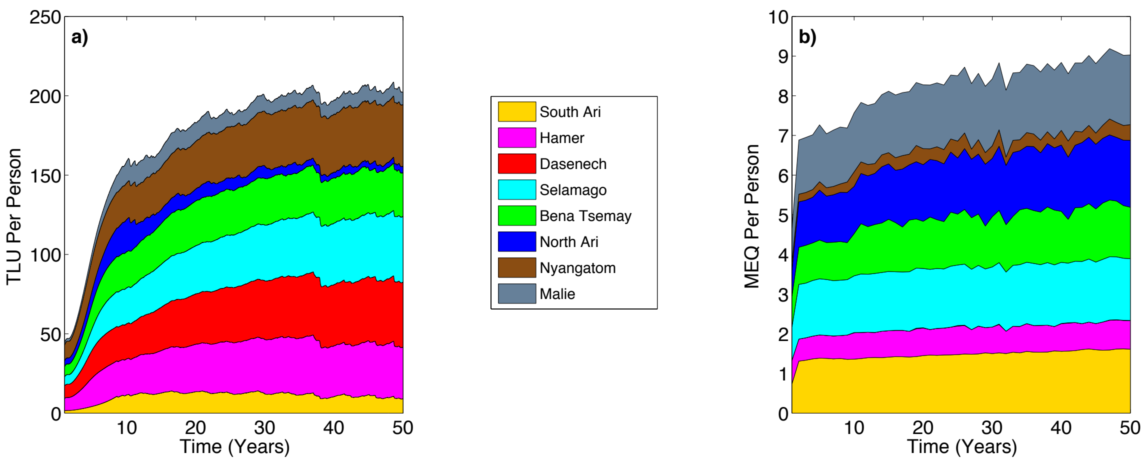


Figure 19: Livestock and crop production with "good year" scenarios by woreda a) number of livestock (TLU) per person per woreda , b) crop (Maize Equivalen -MEQ in kilogram) per person per woreda

In the second experiment, we introduce drought with various intensity and frequency to explore the adaptive capacity of rural households. Figure 20 shows the total population of the zone over time under different levels of drought intensity and frequency. The impact of climatic extreme events on rural households is pronounced as the frequency and intensity increases. When the drought occurs once in 10 to 15 year interval as shown in Figure 20, the impact on total population minimzes even if the drought intensity increases from 50 % to 90%. However, when the drought occurs once in every 5 years, the impact increases and affects the total population growth in the zone. The impact can be seen clearly as we account the number of people who migrate from the system as shown in Figure 21. A change in climate situation can easily affect households that do not accumulate wealth to support them beyond a year and can force them to exit from the system.

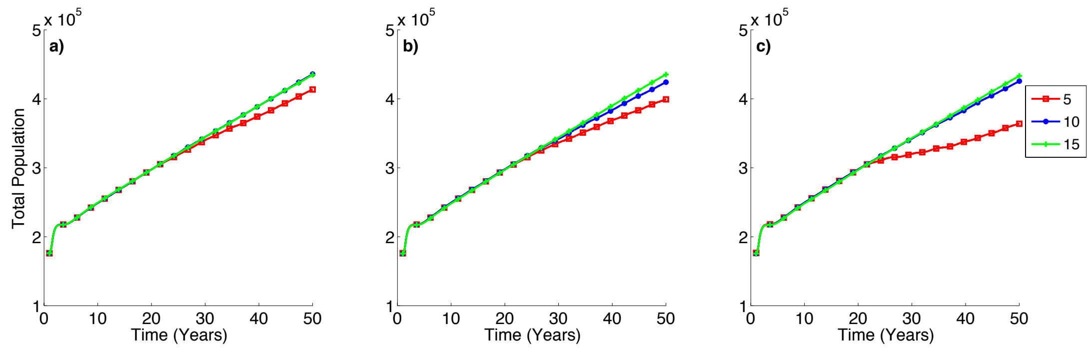


Figure 20: Population growth over time with different climatic condition a) 50 % reduction, b) 70 % reduction, c) 90 % of reduction of rainfall from the mean

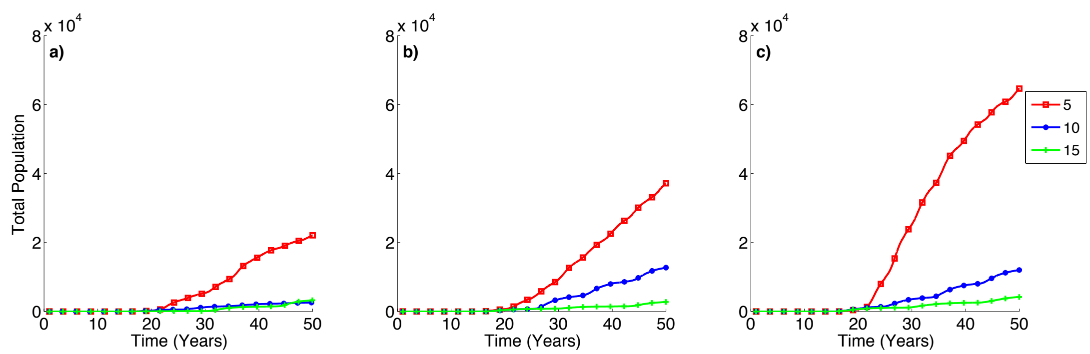


Figure 21: Population migration over time with different climatic condition a) 50 % reduction, b) 70 % reduction, c) 90 % of reduction of rainfall from the mean

The drought also affects the livestock numbers in the system. The change in TLU per person is dramatic as the frequency and intensity increase. Although the drought occurs once in 15 years, the TLU per person dramatically decreases by 30% to 90 % as the intensity increases from 50 % to 90 % as shown in Figure 22a,b, and c. However, as the simulation progresses, the numbers slowly recover and reach 20 TLU per person as a consequence of more good climatic years until another drought year occurs. Another striking result is the impact of drought as it occurs more frequently. As drought occurs once in every 5 years, the number of TLU per person decreases dramatically and is difficult to recover as livestock growth depends on the amount of vegetation available in the surrounding area, which is highly correlated with rainfall amount.

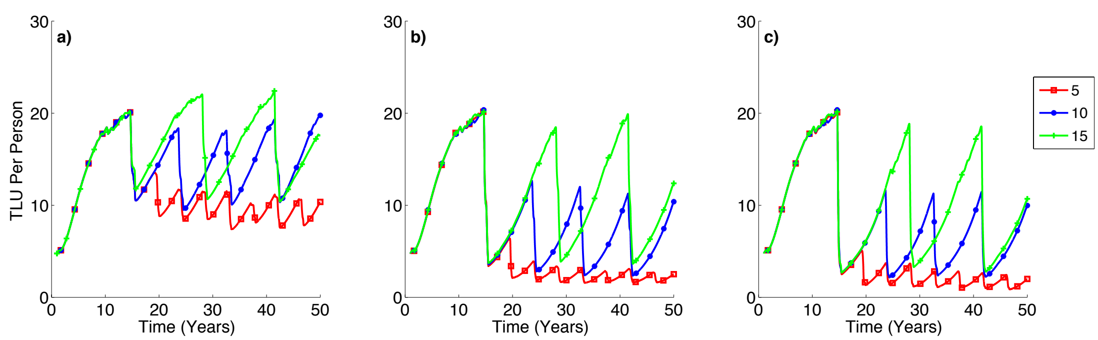


Figure 22: Livestock growth over time with different climatic condition a) 50 % reduction, b) 70 % reduction, c) 90 % of reduction of rainfall from the mean

In the third experiment, we introduce drought that occurs for two consecutive years. Increasing stress in such a way helps to assess the resilience of rural households in the area. As shown in experiment two, a year-long drought affects the rural households as the intensity and frequency of the drought increases. However, in cases where the intensity is low, in time where drought occurs for a short period, rural households are able to pass the "bad year" using their stored capital. However, as the drought lasts longer (from one year to two), it easily affects the asset capital of rural household and forces them to migrate rapidly as the simulation progresses as shown in Figure23 and Figure 24.

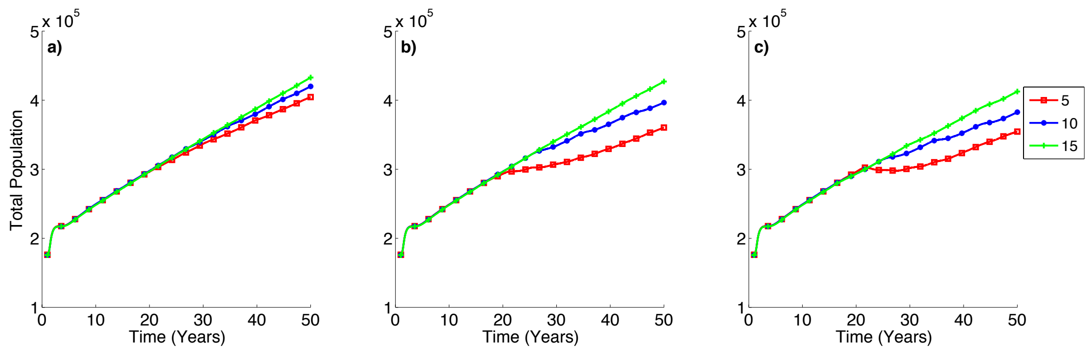


Figure 23: Population growth over time with consecutive drought occurrence a) 50 % reduction, b) 70 % reduction, c) 90 % of reduction of rainfall from the mean

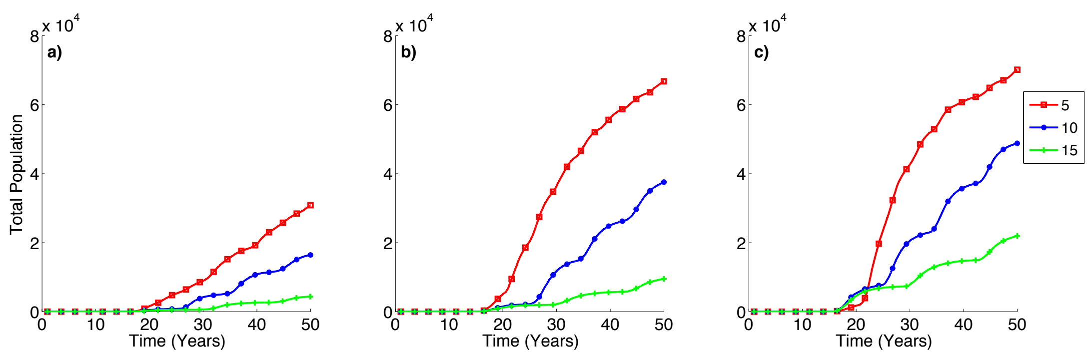


Figure 24: Population migration over time with consecutive drought occurrence a) 50 % reduction, b) 70 % reduction, c) 90 % of reduction of rainfall from the mean

In the real world, climatic condition is unpredictable. The rainfall patterns combine both some good and bad years. Especially in the South Omo zone, the rainfall pattern is erratic with pronounced occurrences of drought. Such erratic rainfall patterns have direct implication for the rural household decision-making and their productive systems, particularly the crop and livestock production systems. The implication can be seen as we observe the model results from “erratic years” scenario runs as shown Figure 25. As Figure 25a indicates, the population and household numbers increase over time as the simulation progresses. However the rate of growth slows down as the number of households migrating from the system increases over time as shown in Figure 25b. Another surprising result is the trend of livestock and crop production in the zone. As indicated in Figure 25c, TLU per person shows a decreasing trend over time while the MEQ per person shows an increasing trend as shown in Figure 25d. The unpredictable nature of the rainfall pattern affects the recovery rate of livestock per household and encourage more households to engage in crop production. However, the crop pattern in the zone is not homogenous. Even in areas where the biopysical and climate conditions are similar, the choice of each household to enage in farming shows siginifcant variation as shown in Figure 26.

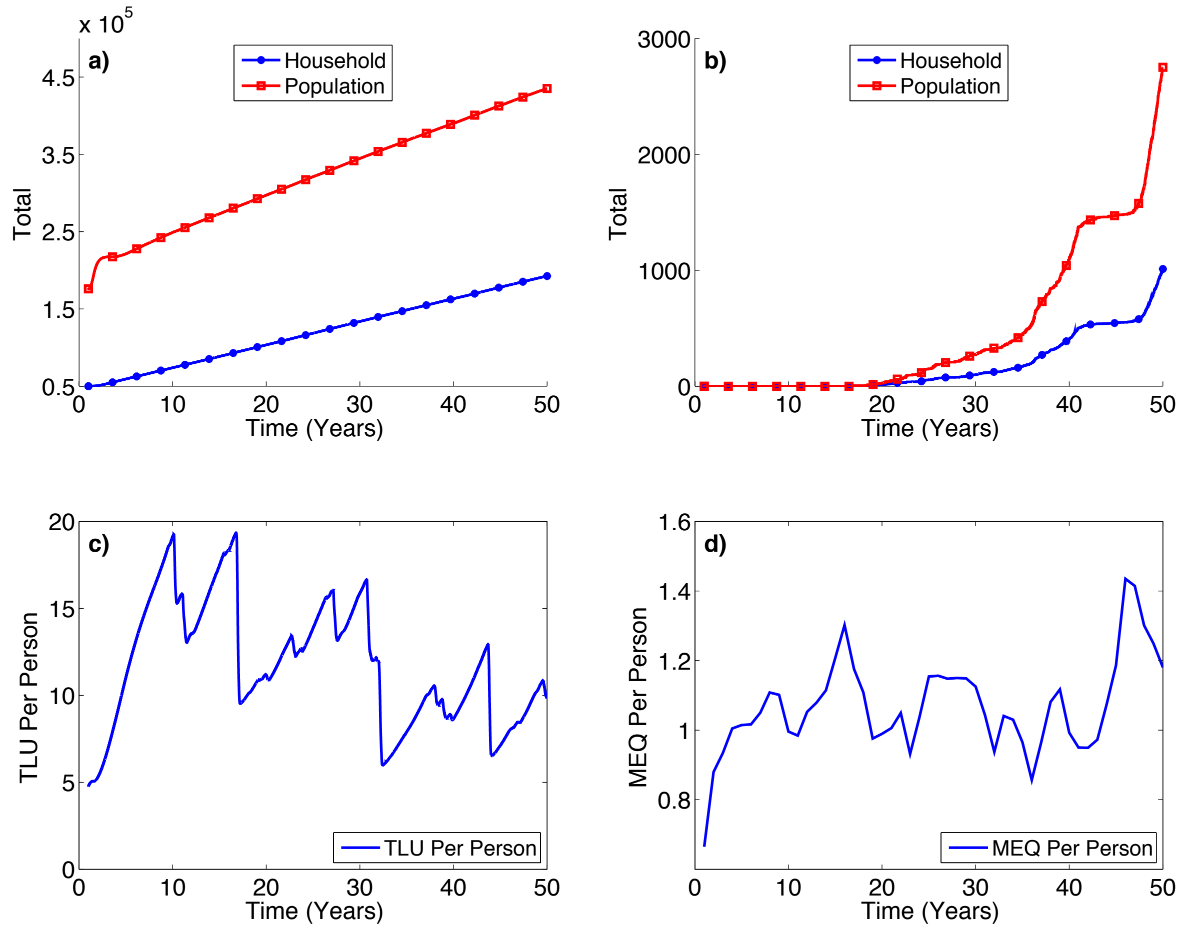


Figure 25: Household dynamics with "erratic climate" scenario
a) household and population number over time , b) number of household and people migrating from the system, c) number of livestock (TLU) per person, d) crop (Maize Equivalent -MEQ in kilogram) per person

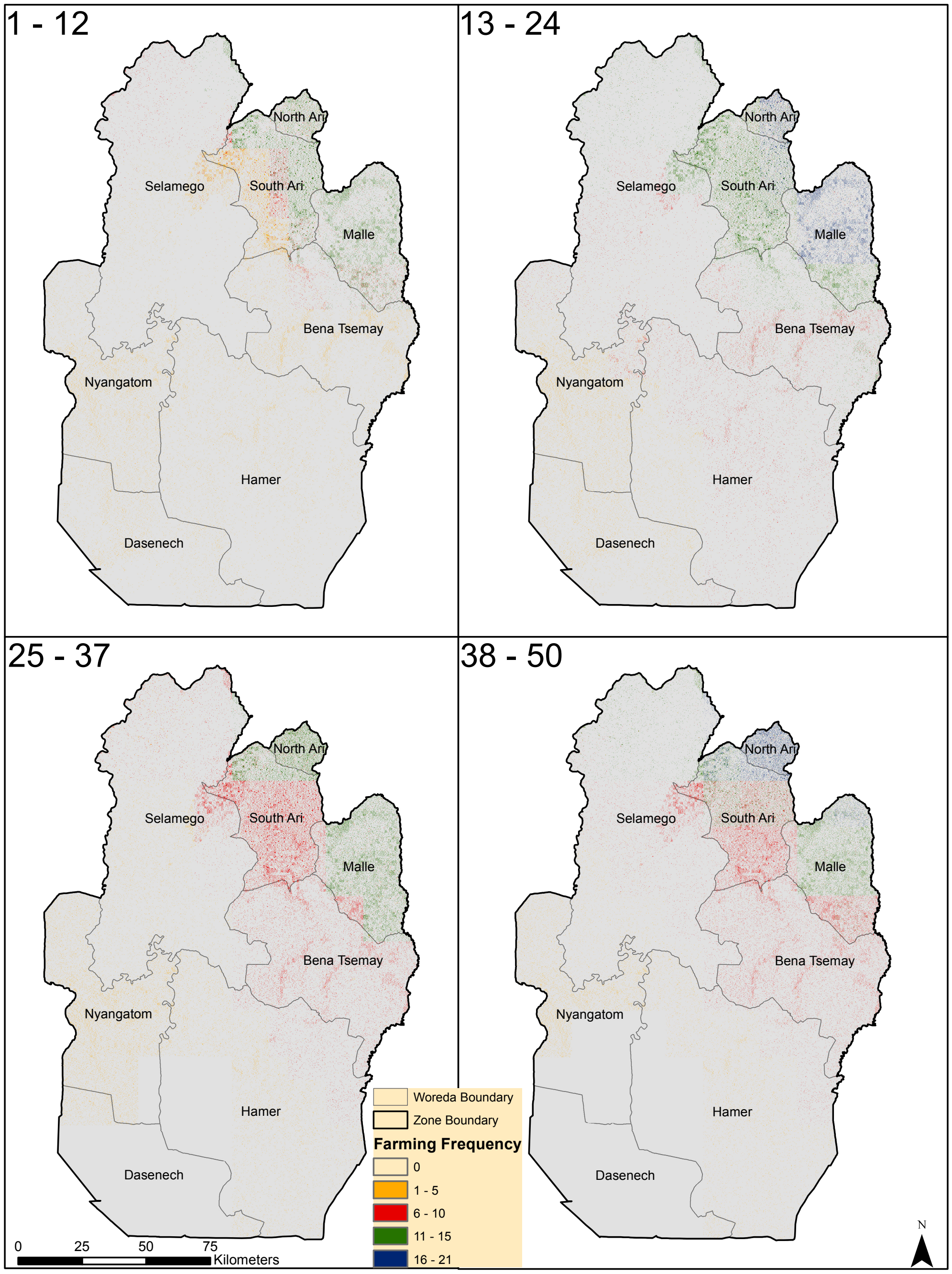


Figure 26: Frequency of farming over 12 years period interval with erratic rainfall scenario

4.2.3 Discussion

Climate change plays a great role in shaping the socioeconomic dynamics of rural households. In the South Omo zone, where the main livelihood depends on rainfed agriculture systems, variation in climate influences the rural household in many ways. The OMOLAND model demonstrates that climate variability influences the equilibrium and dynamics of other relatively stable ecosystems. It also underscores the resilience of the people to rainfall variability, though with its limitations. Change in climate conditions specifically affects the livestock and crop production systems and can trigger population migration if the frequency and intensity of climate extreme events increases. The model also demonstrates that rural households could achieve a strong resource base with relatively continuous good climate years. Such accumulation of resources assists the rural households to withstand droughts with a high degree of intensity as discussed in section 2.3.1.

The magnitude of livestock loss under severe climatic extreme events is not uncommon in a pastoral area such as the South Omo zone. Previous studies [109, 111, 128] indicate that in times of severe drought, livestock losses can reach 90%. For instance, McCabe [109] investigated livestock losses in four pastoral families in Turkana, Kenya, during the drought of 1979-1983, reporting losses of 63% (cattle), 45% (camels), and 55% (small stock) with respect to total family possession before the drought. Moreover, drought can also reduce the number of rural family units by triggering migration. Many rural households who lost their resources due to drought migrated to nearby cities to seek employment [128].

4.3 Theme 2: What are the Impacts of Large-scale Land Acquisition on Rural Households?

The main aim of this experiment is to explore the impacts of large-scale land acquisitions on rural households. The model components incorporate enterprise-household-climate-environment interactions.

4.3.1 Experimental Scenarios

We perform a set of experiments with OMOLAND in order to examine the impacts of enterprises on rural households. We particularly focus on exploring whether the introduction of enterprises in rural systems increases the vulnerability of rural households or provide the rural households an opportunity to diversify their livelihood options by engaging in off-farm activities. We look into the following two main experiments: (a) large-scale land acquisition with no off-farm opportunity, and (b) large-scale land acquisition with off-farm opportunity.

In the first scenario we allow the expansion of large-scale land acquisition in the systems with different intensity but with no opportunity of off-farm activity for the rural households. Our main interest is to assess the issues related to commercial enterprises' contribution to provide additional off-farm opportunities to rural households. Although commercial enterprises increase employment opportunities, the chance of rural communities to participate in these employment opportunities is not guaranteed due to high competition. Moreover, the jobs are often short-term or seasonal and were usually poorly paid (partly because of the local people's lack of skills) [140]. Such factors discourage the engagement of rural households in off-farm activities and affect the possibilities of rural households getting benefits from off-farm opportunities. Hence in this scenario, we introduce enterprises but with no off-farm opporunities.

In the second scenario, we allow the enterprise to open up labor employment opportunity to the rural households [36]. In this scenario, enterprises recruit and dismiss employees depending on their labor requirements. Rural households search any off-farm opportunity open by enterprises in their vicinity and participate if they have any extra labor remaining from livestock and crop management or if ether of the two activities does not provide enough income for the household. In both scenarios, we examine two types of intensity of expansion. The first intensity is a slow growth of expansion of enterprise with 2% annual growth rate, while in the second we explore a fast expansion growth rate of 5%, which represents the current trend in the dynamics of land acquisition in the zone.

In each experiment, two types of agents, the rural households and the enterprises, are considered as main agents. In this experiment, there is no representation of institutions in this model setting. The simulation runs for 18,250 iterations (each iteration step is a day and 18,250 iterations are about 50 years). In each experiment, we have a normal climatic condition for the first 3 years so that the model initialization stabilizes. We then introduce the real climate data in the same way as we used in section 4.2 for "erratic rainfall" scenario. We run a set of 30 simulations with a constant initial parameter setting, which is the default value of the parameters.

4.3.2 Results

The "no off-farm opportunity" scenario indicates the household and population number grows throughout the simulation period in both 5% and 20 % land expansion rate as shown in Figure 27.

Table 6: Land expansion with "no off-farm opportunity"

Type	Annual Land Expansion Rate	
	2%	5%
Household	178,629	175,748
Population	415,431	411,413
Emigrants	2,935	6,594
Commercial land (Ha)	28,430	124,801

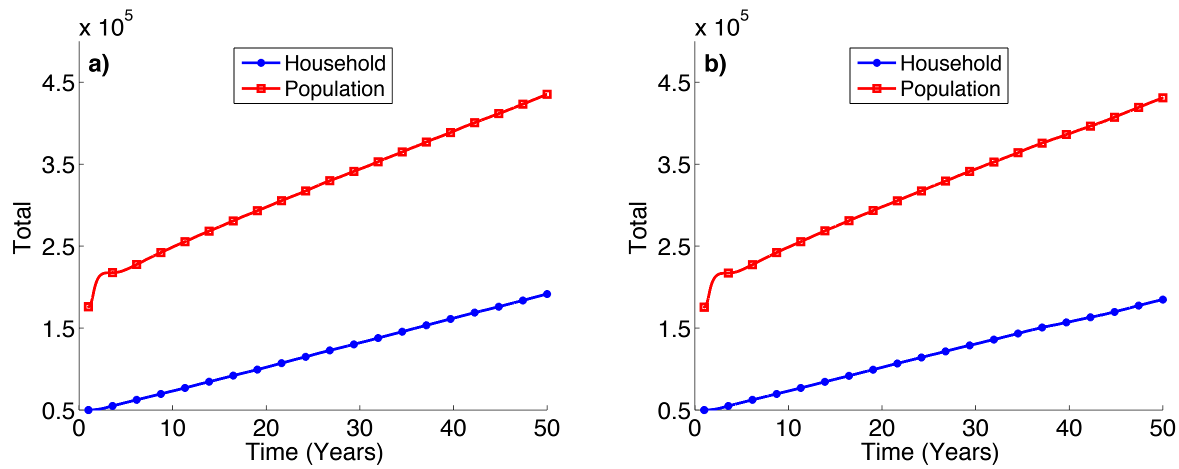


Figure 27: Household and population growth with "no off-farm opportunity"
a) 2% annual expansion rate , b) 5% annual expansion rate

When we explore the number peoples migrates from the system, we observe that there is significant difference between the 2% and 5% expansion rates especially in the last 10 years of the simulation. However, the change in migration numbers is not linearly related with the change in the rate of expansion of large-scale land acquisition. As shown in Figure 28, at the end of the simulation, the number of peoples migrate reach to 1 person for every 9.7 hectare of land acquired by enterprise at 2% expansion rate, while in the 5% rate of expansion, the number of people migrating is lower to 1 person for every 18.9 hectare of land acquired by enterprise.

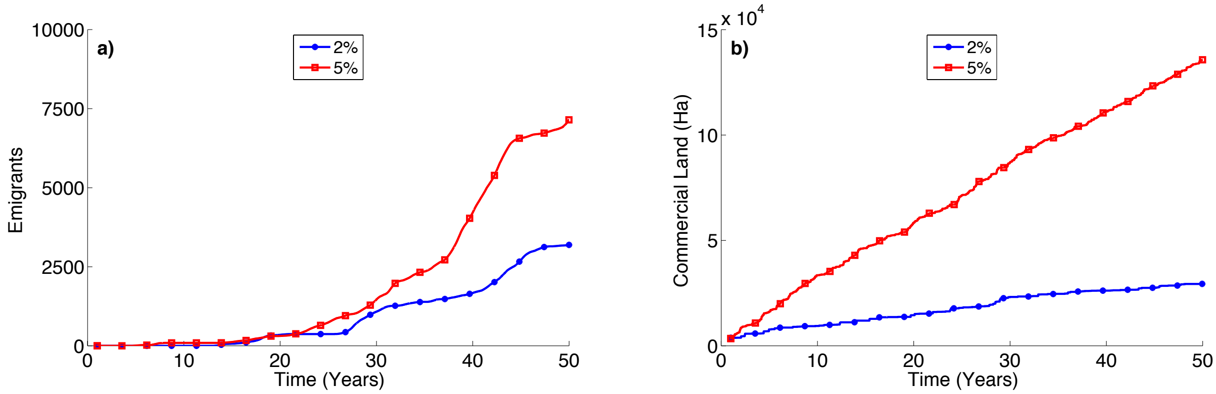


Figure 28: Migration and land expansion with “no off-farm opportunity” a) total number of people migrating from the system, b) area of land acquired by enterprise in hectare

We also explore the impact of expansion of large-scale commercial farming over time on crop and livestock production. It is interesting to observe that increasing the rate of expansion of large-scale commercial farming does not significantly affect the per capita level of livestock and crop production in the zone. In both rates of expansion (2% and 5%), the trend in livestock and production along the simulation period are not significantly different. However, in both cases, the livestock production shows a slight downward trend while crop production shows a slight upward trend. This might be due to the fact that most of the land that has been assigned for the enterprises are located in areas where livestock production is the dominant production system.

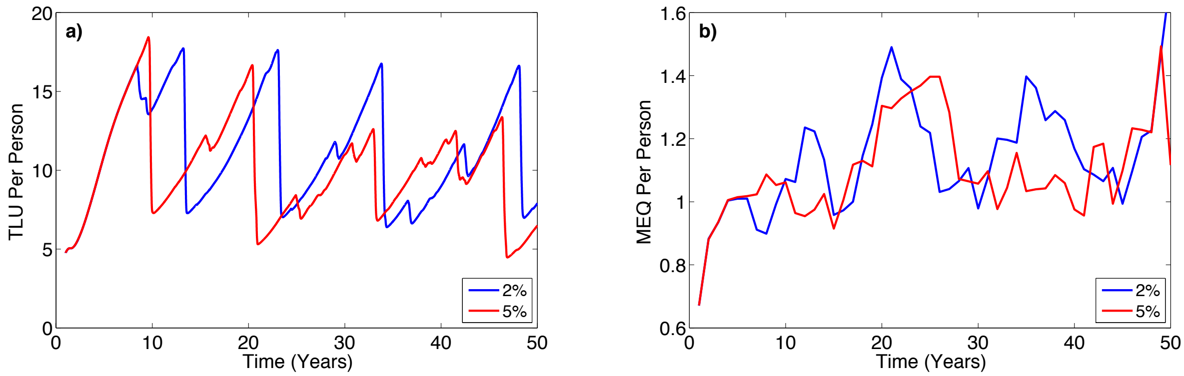


Figure 29: Livestock and crop production with "no off-farm opportunity" a) number of livestock (TLU) per person, b) crop (Maize Equivalen - MEQ in kilogram) per person

When we allow enterprises to open employment opportunities for the rural households, the simulation model provide a different result in the number of people migrating from the system, and in the pattern of livestock and crop production. As shown in Figure 30a, the total number of people migrating from the system decreases significantly as compared to the "no off-farm opportunity" scenario. Along wit the expansion of large-scale commercial farming, the number of people who are engaged in off-farm activity increases as the simulation progresses as shown in Figure 31b.

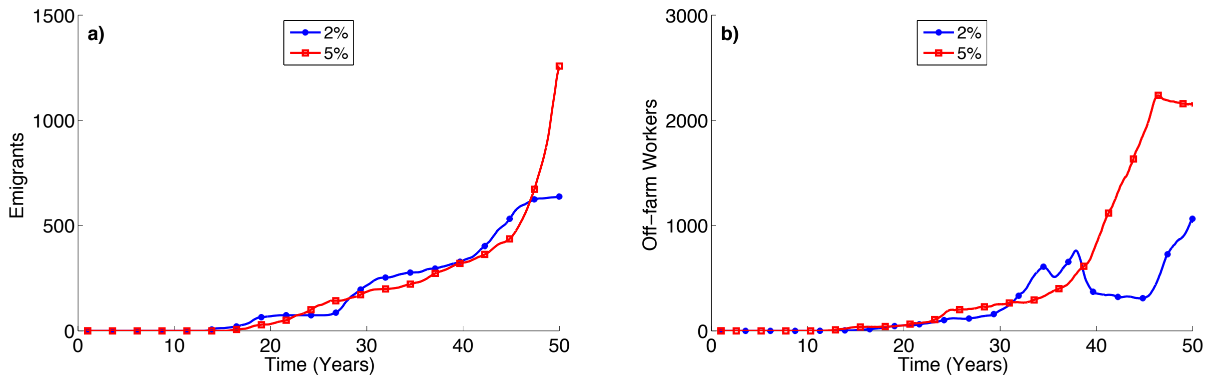


Figure 30: Migration and off-farm activity with "off-farm opportunity" a) number of people migrating from the system , b) number of people who are engaged in off-farm activity

Although engaging in off-farm activity provides additional income to the household, the existence of off-farm opportunity does not entirely eliminate the migration trend of rural households even with strong presence of enterprises (5% growth rate) since there are still people who cannot sustain their livelihood under the current climatic conditions and are forced to leave the system.

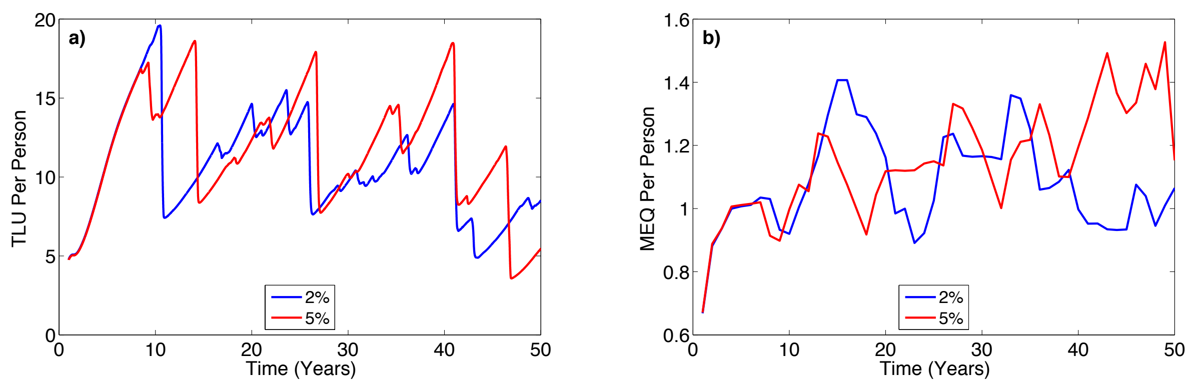


Figure 31: Livestock and crop production with "off-farm opportunity" a) number of livestock (TLU) per person, b) crop (Maize Equivalen - MEQ in kilogram) per person

The opportunity of engaging in off-farm activity affects the amount of both livestock and crop per capita but differently. As shown in Figure 31, the TLU per person shows a downward trend while MEQ per person shows an increasing trend as the simulation progresses. Comparing the two scenarios, the trend in both livestock and crop production is more pronounced in the second scenario than the first scenario. The TLU per person that reaches a level of 20 ten years after the start of the simulation goes down to less than 5 TLU per person by the end of the simulation in the second scenario, while it was more than 7 in the first scenario. Similarly, the MEQ per person increases from 1 to 1.6 by the end of the simulation in the second scenario, which is almost increased by 20% as compared to the first scanrio.

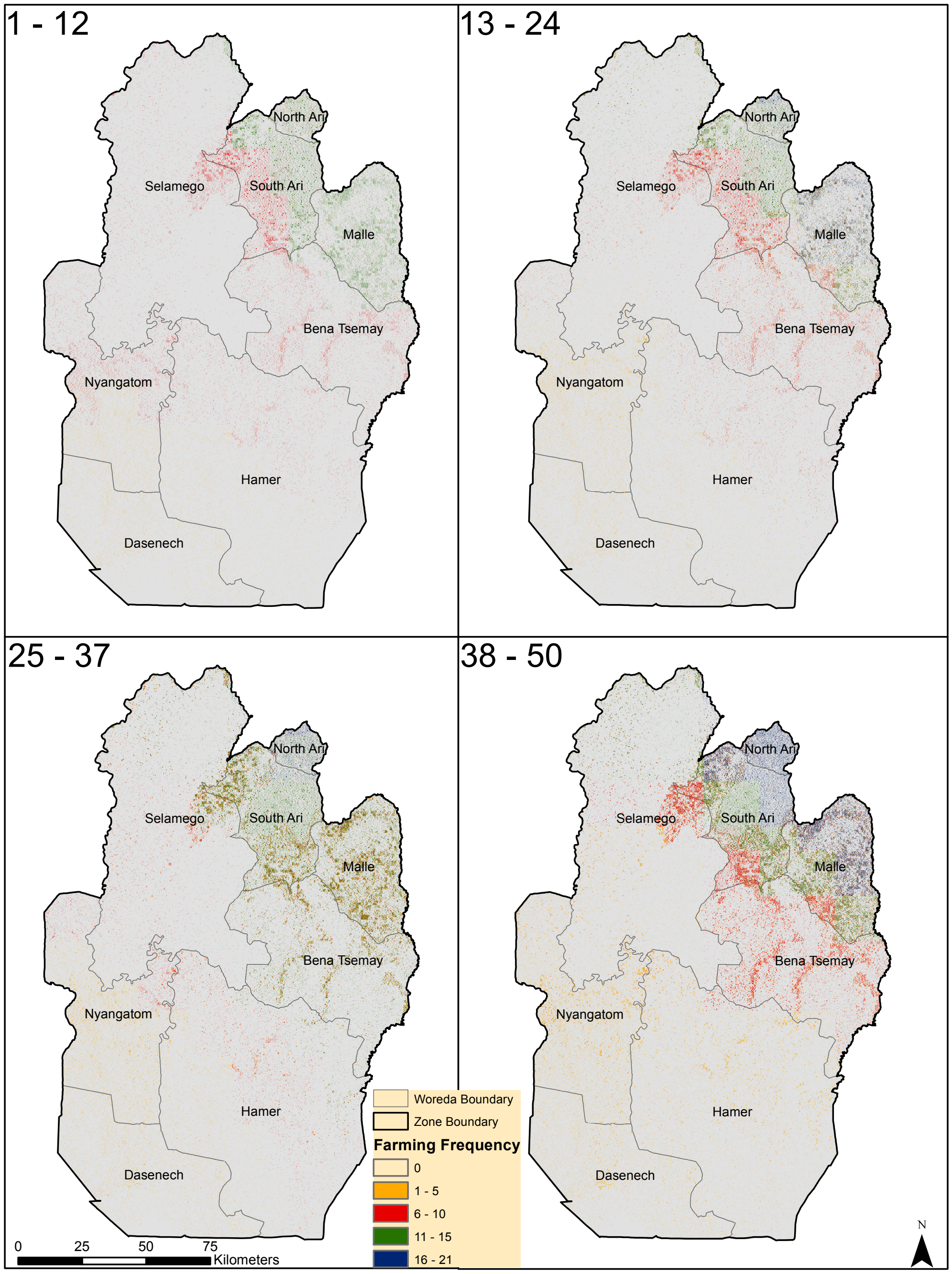


Figure 32: Frequency of farming over 12 years period interval with with “off-farm opportunity”

4.3.3 Discussion

Our model demonstrates two important points on the impact of large-scale land acquisition in rural systems. First, it indicates that land acquisition without any opportunity can lead to catastrophic outcomes as more people are forced to migrate from the system[121, 126]. Although migration of rural households can occur due only to climate extreme events, the model results demonstrate that migration rate can be exacerbated as more lands that have been utilized by rural households are given to enterprises. Second, the model demonstrates the impact of off-farm opportunities generated by enterprises on rural household livelihood. At first glance, it seems that the results align with the aspiration of government intervention or with those who advocate economic contribution of enterprises in the rural systems [36, 155]. The emergence of additional sources of income influences the way in which rural people react to climate variability. As more people engage in off-farm activities, particularly in time of drought, their vulnerability is reduced by the income they can generate from off-farm activity. However, close observation of these result indicates that migration still continues to happen as more lands are taken by enterprises as discussed in section 2.3.2.

Another striking model result is the gradual livelihood transition of rural household from livestock to crop dominating livelihood as more enterprise are introduced in the system. Galvin [66] argue that pastoral transitions in most East African countries are attributed by two major factors. First is the fragmentation of grazing land, which is caused by a number of socioeconomic factors such as changes in land tenure, agriculture, and institutions. Second is climate change and climate variability mainly due to the occurrence of extreme events such as drought. Although the model needs further comprehensive assessment, the simulation results agree with these trends as more household have engaged in farming than livestock production as most of the grazing lands are converted into commercial farming over the simulation period.

4.4 Theme 3: What are the Impacts of Institutional Interventions on Rural Households?

In this experiment, we explore the impact of institutions on rural systems particularly by providing support to rural households through capacity building and relief support in time of drought. The inclusion of institutions adds another complexity the OMOLAND model, with this representation, the OMOLAND model captures all the components of the rural systems as it is described in section 3.4.

4.4.1 Experimental Scenarios

We allow the institution to provide a relief support to the rural household in time of drought to minimize their rate of migration. We assess the impact of provision of climate change adaptation capacity building (training) to rural households. We perform two expriments.

In the first experiment, the insitution targets to build the capacity of 5% of the total households over 50 years of the simulation period. In the second, we raise the target to 20% over 50 years of the simulation period. Rural households can get the capacity building once or multiple times over the simulation period. The selection of the training is random. This intervention allows the rural households to learn more about climate change adaptation and increase their self-efficacy, which ultimately affects their adaptation appraisal as discussed in section 3.6.3.3.3. In each experiment, we allow the enterprise to open up labor employment opportunity to the rural households as discussed in section 4.3. The simulation runs for 18,250 iterations (each iteration step is a day and 18,250 iterations are about 50 years). We keep the first 3 years to have a normal climatic condition similar to Theme1 and Theme 2 settings. We run a set of 30 simulations with a constant initial parameter setting, which is the default value of the parameters.

4.4.2 Results

Before presenting the experimental result on rural household adaptation, we first present how rural households make predictions and how rural households' judgment aligns with the real seasonal rainfall outlook. As shown in Figure 33a, almost throughout the simulation period, more than 60 % of the rural households predict the onset of rainfall as late onset while the rest predict the seasonal outlook of rainfall as normal or early onset. When we compare how much their prediction aligns with the real seasonal pattern of the rainfall, the proportion significantly declines to below 50 % in most simulation periods with a few exceptions as shown in Figure 33b.

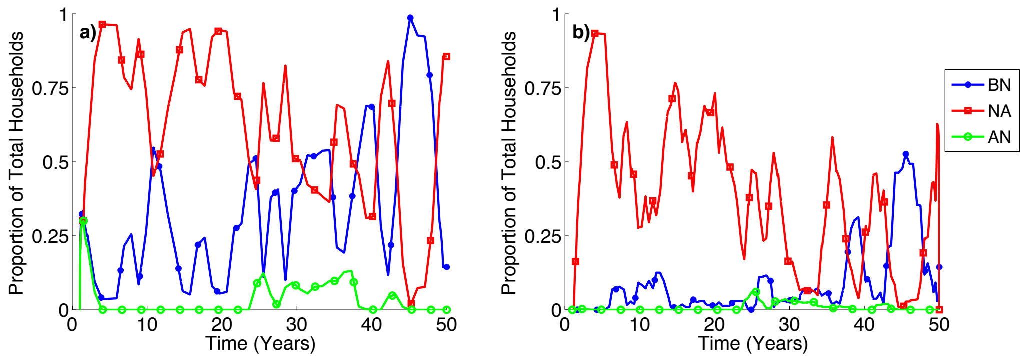


Figure 33: Rural household onset prediction
a) seasonal onset prediction by households, b) proportion of household correctly predict seasonal onset

The prediction of the amount of seasonal rainfall is shown in Figure 34. In the first 30 years of the simulation period, the proportion of households that predict seasonal rainfall as normal accounts for more than 50 % of the total households. However, the number drops significantly after 30 years as most of the households assume the rainfall amount likely to be below normal. The level of accuracy of household prediction on the amount of rainfall, however, shows a decline trend as the variability of the rainfall increases over time. As indicated in Figure 34b, the proportion of rural household that actually predict correctly based on past experience is higher in the first 30 years than in the last 20 years.

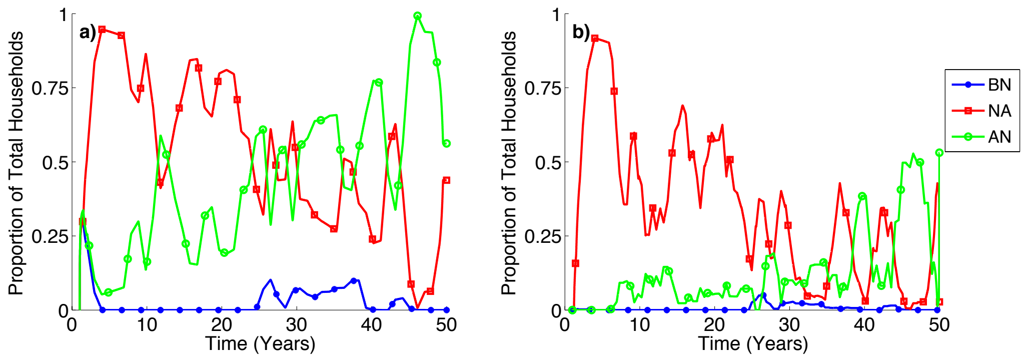


Figure 34: Rural household amount of rainfall prediction
a) seasonal amount of rainfall prediction by households, b) proportion of household correctly predict seasonal amount of rainfall

We explore the adaptive response of rural households to the seasonal variation for climate as the institution provides more support through capacity building. Figure 35 shows the proportion of rural households adopters (those who implement climate change adaptation measures), the proportion of rural household non-adopters (those who do not apply any climate change adaptation measures), and the average adaption experience of the households. As shown in Figure 35, when the coverage of training increases from 5% to 20%, the number of households who implement climate adaptation measures increases significantly. It is very intuitive to observe the relation between provision of climate change adaptation awareness and rural households' adaptive reponses. However, the response is not immediate. Although rural household's level of climate change experience increases as they are exposed to adaptation training or information, they can be easily constrained by various factors to objectively implement adaptive measure(e.g household perception of risk, household wealth status, household size, etc.) as discussed in section 2.3.1.

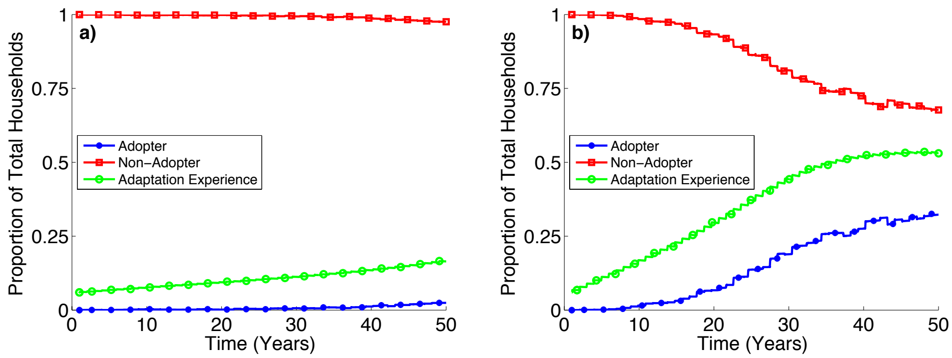


Figure 35: Climate change adaptation response by rural households
a) Climate change adaptation at 5% coverage, b) Climate change adaptation at 20% coverage

We also explore the impact of institutional intervention on the overall success of rural households. As shown in Figure 36, the combination of relief support and opportunity for off-farm activity significantly minimize the rate of migration from the system. Moreover, increase in climate change adaptive capacity of the rural household increases the number of people who engage in off-farm activity as shown in Figure 36.

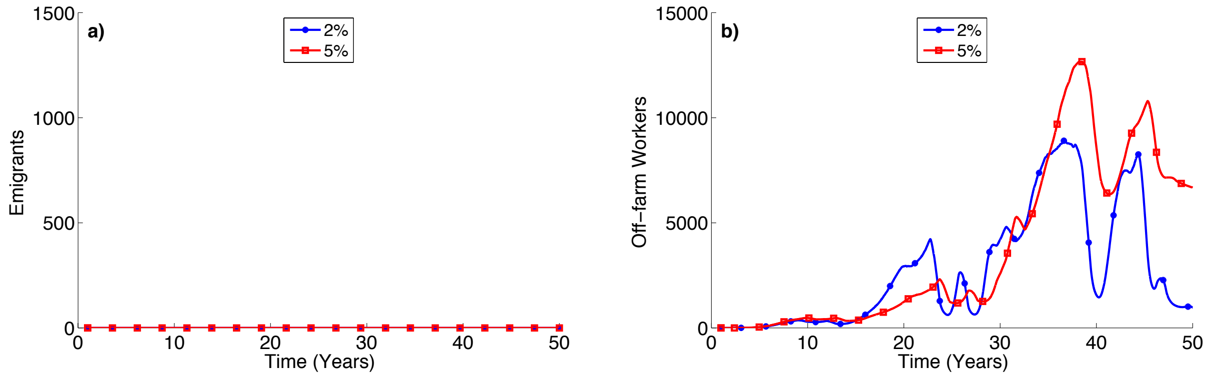


Figure 36: Migration and off-farm activity with "off-farm opportunity" with institutional support

a) number of people migrating from the system , b) number of people who are engaged in off-farm activity

Another implication of enhancing climate adaptive capacity and more extra income opportunity, either through relief or off-farm opportunity, can be seen in the level of livestock and crop productivity of the rural households. As Figure 37 indicates, the livestock production per capita decline as the simulation progresses while crop production per capita shows a slight increase.

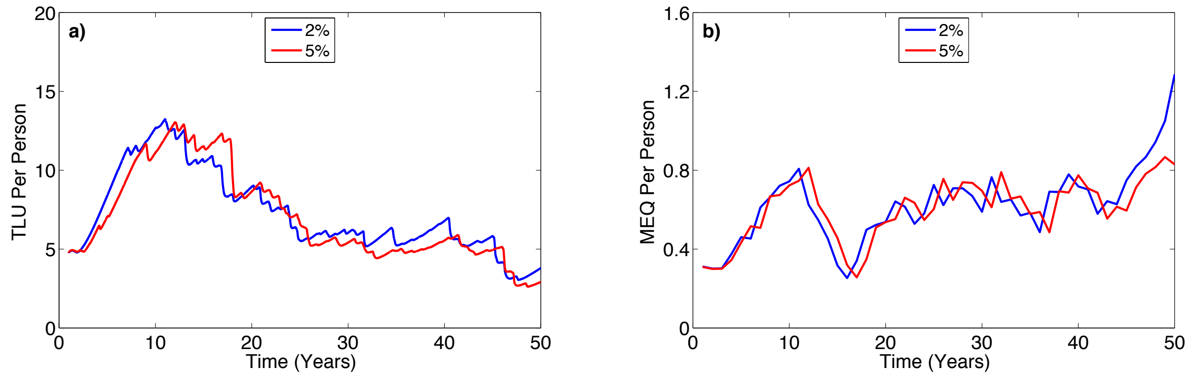


Figure 37: Livestock and crop production with 'off-farm' opportunity with insitutional support
a) number of livestock (TLU) per person, b) crop (Maize Equivalen - MEQ in kilogram) per person

4.4.3 Discussion

Although the representation of institutions in the OMOLAND model is very simple, the outcome of the model can shed light on the intricate issues related to rural households, enterprises, and the biophysical environment.

Rural households utilize different mechanisms to forecast the onset and amount of seasonal rainfall as discussed in section 3.6.3.3.3. In most case, they base their prediction on rainfall pattern of previous years [103]. As discussed on section 3.4, in the OMOLAND model, a rural household forecasts the seasonal rainfall based on three pervious years of rainfall of that season. Due to limited access to public climate prediction information and high dependency on their traditional prediction methods, the chance of the rural household forecasting the rainfall onset and amount accurately is very low. Such an information flaw ultimately affects the way the rural households respond to climate variability.

As discussed in section 4.3.2, the emergence of off-farm opportunity by itself does not entirely eliminate the migration of rural households as climate variability intensifies. However, the involvement of institutions in the rural system plays a significant role in minimizing the vulnerability of rural households. The opportunity of getting access to relief or similar support, in addition to off-farm opportunities in time of drought helps the poor rural households to continue to dwell in the system as discussed in section 2.3. However, such opportunity by itself does not enhance livestock and crop production per capita.

4.5 Conclusion

We presented various model results on the three themes of this dissertation. These results could provide better insight on the complex interaction of rural households, enterprises, and institutions, as well as the biophysical environment under different climate scenarios in the South Omo zone. The resilience of the rural systems is not influenced by large-scale enterprise alone but by a combination of factors such as climate variability, household adaptation capacity, the biophysical suitability, and rural households' access to off-farm opportunity. Although further research is needed to explore more on the complexity of rural systems, these simulation results demonstrate that the model displays plausible overall behavior.

5 DISCUSSION

5.1 Introduction

This section synthesizes the main findings, the broader scientific implications, and policy implications of this dissertation. In the final section, we present some perspectives for future research. As Morton [119] writes, the impact of climate change will arguably be felt among rural households predominately located in the tropics as their livelihood depends to a great extent on climate-driven agricultural production systems. The impact will likely be aggravated by changes in rural systems, especially by ongoing large-scale land acquisition by different agribusiness enterprises. Assessing the social consequences of large-scale land acquisitions in rural systems, given a range of scenarios in regional climate change, economic, and policy changes is a complex task. Understanding the complexity of rural systems requires developing improved methodology that explicitly represents the main components of the systems (human and natural) and captures the ways these components are interacting and affecting each other on various temporal and spatial scales. The findings of this dissertation are therefore two fold: those relevant to the rural systems of the South Omo zone, and those related to methodological aspects.

5.2 Recapitulation of Main Results

The first chapter highlight the magnitude of current large-scale land acquisition Sub Saharan Africa, particularly in Ethiopia, and explains the need to explore the impacts of such land investment on rural livelihoods, given that the system is already stressed by climate variability as discussed in section 1.2.

The second chapter provides the context of the South Omo zone. The South Omo zone communities have been under different climatic stress for many generation and have been able to survive by developing different adaptation mechanisms. Their choices of livelihood and distribution on the landscape are determined by the heterogeneity of the biophysical environment and by climate variability. It also highlights the fact that the major challenge they are currently facing is a compound effect of climate variability and the expansion of large-scale land acquisition as discussed in section 2.2. These challenges are not limited to the South Omo zone, but happen in many rural systems in Sub Saharan Africa as discussed in section 2.3. The chapter also showed that the complexity of factors playing roles in understanding the impact of climate variability and the consequence of large-scale land acquisition in rural systems demands the development of a comprehensive methodology that integrates the different components and adaptive behaviors of rural households as discussed in sections 2.3 to 2.5.

In the third chapter, we showed how we represent the complexity and dynamics of rural system of the South Omo Zone by conceptualizing the system as complex adaptive system and identifying the major components that are currently playing significant roles in shaping the system. We built OMOLAND, which is a spatial agent-based model that explicitly represent the main components of rural system (households, enterprises, institutions, climate, and biophysical environment), their interactions, and dynamics using existing understandings of complex adaptive systems, climate change adaptation, coupled human and natural systems, and GIS, which have outlined in section 2.3. This approach to modeling consequences of climate change and large-scale land acquisition in the South Omo is unique as it incorporates the major components of rural systems in a single model and also explicitly represents the socio-cognitive decision-making of rural households, capturing the interaction of the biophysical environment and climate change by using multi-temporal rainfall data to capture the vegetation and crop growth dynamics. Our model adds to the growing body of literature in the field of coupled human and natural systems that uses spatial agent-based modeling to aid our understanding of the complexity of rural systems as discussed in section 2.4. We also implemented different techniques to verify and validate the model as discussed in section 3.7.

We present the simulation results in chapter 4. The model suggests that rural households' adaptation to climate change is highly influenced by their adaptive capacity and their expectation of future climatic situations. While the rural communities in the South

Omo zone are better off in normal climate conditions, they can persist if the climate conditions continue with the current trend. The occurrence of successive episodes of extreme events even after good climatic years, however, results in substantial damage to their assets (livestock and crops) and consequently affects their adaptive capacity and forces them to migrate out of the system in greater numbers as discussed in section 4.2.

Moreover, the model result also indicates that the introduction of commercial enterprises in rural system can minimize rural households' vulnerability to climate variability through opening up off-farm opportunity to some extent. However, increases in the magnitude of dispossession of land property aggravates the disparity and inequality between rural households as the system transits to new phases as discussed in section 4.3. The intervention of institutions through capacity building and relief support in the time of extreme events minimizes the number of people migrating from the system. Increasing the awareness of the rural household to climate variability helps them to increase their productivity and choice of livelihoods. However, as more lands are converted to commercial farming over time, the adaptation capacity of the rural household does not sufficiently reduce the impact of climate variability unless additional livelihood options are offered to rural households as discussed in section 4.4.

5.3 Broader Scientific Implications

We believe this dissertation is the first to investigate the combined impact of climate change and large-scale land acquisitions in developing countries. Moreover, by using an agent-based modeling approach, the study serves as a foundation for analyzing similar phenomena in other parts of the world (e.g., Sub-Saharan Africa, south Asia, Latin America). To assess the consequences of ongoing large-scale land acquisitions on rural households and how interaction between rural households and enterprises affect the rural systems, we believe it is essential first to address how rural communities adapt to climatic variation to sustain their livelihood, and what may be their capacity to prevail in the face of future climate change scenarios.

Although socio-cognitive components play the largest role in understanding societal adaptive responses to climate change, the extant literature shows that previous models either exclude the representation of socio-cognitive behavior of households altogether or they greatly simplify the adaptive behavior and responses of households. Therefore, our model, which incorporates a socio-cognitive representation of rural households, will shed new light on understanding the consequence of climate variation on rural societies through the medium of simulated experiments and scenario analyses as highlighted in section 3.6.3.3.3.

Our modeling approach complement current efforts aimed at integrating GIS and agent-based models, a significant methodological thrust in computational social science and geospatial modeling. The OMOLAND model utilizes various spatial datasets to represent the different model entities. The model utilizes GEOMASON facilities to export model outcomes to GIS readable formats so that it can be easily further analyzed in GIS software environmnet as discussed in section 3.5.

We have presented our findings to the broader scientific community, regional agencies of global policy-making institutions (e.g., UNEP, WFP, UNECA), and have received positive feedback. The conceptual model and the first part of the model were presented in scholarly conferences for computational social scientists, geographers and natural resource managers [78–80]. The final model outcomes also were presented to scientists and local and global policy-making institutions in Addis Ababa, Ethiopia [81].

5.4 Policy Implications

In this dissertation, we integrate theories and methods from social psychology, geography, environmental science, and computational social science to address the complex issues of climate change adaptation and impact of large-scale land acquisitions in rural systems as discusseed in chapter 2 and 3. It will also contribute new ideas on rural systems to improve understanding of policy effects and social consequences. We believe that the integration of concepts, theories and methods from different disciplines will strengthen multidisciplinary efforts and provide a way to develop a more comprehensive policy to alleviate the adverse impact of climate change and commercial land acquisitions on rural systems.

We have explored specific policy-related questions that might be pertinent to the study area and other similar areas. For instance, we showed the importance of institutional intervention through provision of capacity building to rural households to reduce their vulnerability to future climatic shocks. These experimental scenarios demonstrate the potential of computational methods to develop more appropriate policy options that might benefit rural systems. In addition, our OMOLAND model is equipped with a strong visualization component and integrates user-friendly features that can be used by policymakers to test the outcome of climate change and expansion of commercial enterprises as discussed in section 3.6.2.1.

5.5 Future Research

In this dissertation, we represent the complex interaction of land users (rural households and enterprises), institution, and the environment (biophysical, climate and built) in the rural system of the South Omo zone of Ethiopia. Our level of detail on the representation of each component, however, is different. Since the main focus of this dissertation was on rural households, the representation of rural characteristics and adaptation behavior, and their interaction with biophysical environment and climate, were designed in more detail as compared to the representation of enterprises and institutions. To grasp the complexity of rural systems in a more comprehensive way and to maintain the sustainability of the natural resources in the rural systems, a more detailed representation of the characteristics of enterprises and institutions (traditional rural institutions, socioeconomic and political institutions) is essential. Hence, there is plenty of opportunity to expand the current model in future research.

Within the current status of the OMOLAND model, one potential research direction is to conduct comparative analysis of different rural systems that are currently challenged by the impacts of large-scale land acquisitions. As rural systems are complex and each rural system may have distinct biophysical, socioeconomic, and cultural settings, the interaction between different components of the rural systems on different spatial and temporal scales and the emergence of landuse patters in each rural system could be different. Hence, it could be interesting to explore different rural systems and explore the similarity and differences in each system to have better understanding of the impacts of large-scale land acquisition in the rural system context.

Another direction for model extension is to incorporate greater behavioral representations of rural households wth regards to seasonal climate outlooks, and adaptation strategies. For instance, it is interesting to explore the willingness of rural households to adopt new agricultural technology and climate adaptation measures as rural systems would likely be influenced by the emergence of new technologies, market opportunities, financial incentives, and landuse policies [91]. It might be also interesting to explore rural households' trust and their reaction to information on seasonal climate outlook particularly from meteorological centers. As Bharwani et al. [23] indicate, better information on seasonal climate outlook could play an important role in the adaptation responses of rural communities in Limpopo, South Africa. Hence, the work of Bharwani et al. [23] could be used as a starting point to represent information flows and trust formation in the rural communities of the South Omo zone and other rural communities.

The current trends on large-scale land acquisition seems likely to continue over the next decade in most of Sub-Saharan Africa. Hence, exploring the implications of commercially oriented farming systems, not only on rural households but on the biophysical environment, could be another potential extension of the model. As discussed in this dissertation, recently, large tracts of rural lands have been given to a variety of enterprises with competing interests, ranging from those who are interested in commercial farming (food crop and biofuel production) to those who would like to engage in ecotourism. More demand for rural land would likely increase the land value and trigger more land marketing. Hence, it might be interesting to explore the issue of competition of lands between different entities by incorporating a more comprehensive land marketing mechanism (e.g Filatova et al. [63]). Therefore, an integration of land markets or land transactions into the model could help to further understanding of rural landuse changes, socioeconomic transformations, and issues related to rural-urban linkages. Although from the above discussion, it is clear that many avenues of future research are possible, this dissertation plays an important role in investigating these issues and laying the foundation for rigorous work that captures the complex dynamics of coupled human and natural systems.

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