



SEEK WISDOM, ELEVATE YOUR INTELLECT AND SERVE HUMANITY!



Addis Ababa University

College of Business and Economics

Department of Economics

**Modeling the Impact of Climate Adaptation Policy on Major Crop
Production: A System Dynamics Approach**

**Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Economics (Applied Economic Modeling)**

By: Adam Fisha

Advisor: Mengesha Yayo (PhD).

June 2025

Addis Ababa University

Addis Ababa

Addis Ababa University

School of Graduate Studies


Approval Sheet

This is to certify that the thesis prepared by Adam Fisha Melku, titled “Modeling The Impact of Climate Adaptation Policy on Major Crop Production: A System Dynamics Approach” and submitted to the Department of Economics, Addis Ababa University in partial fulfillment of the requirements for the Masters of Science in Economics (Applied Economic Modelling) complies with the regulations of the university and meets the accepted standards for originality and quality.

Signed/approved by;

Internal Examiner Dr. Zerayehu Sime Signature  Date _____

External Examiner Agimasie Demewoz (Msc) Signature _____ Date _____

Supervisor Dr. Mengesha Yayo Signature  Date _____

Acknowledgements

With profound gratitude, I first acknowledge Almighty God and His mother, St. Mary, for their divine grace and blessings that have sustained me throughout this academic journey. Their spiritual guidance has been my constant foundation and source of strength.

I wish to express my deepest appreciation to my esteemed supervisor, Dr. Mengesha Yayo, whose exceptional mentorship, scholarly guidance, and unwavering encouragement were invaluable in the completion of this research. His expertise, patience, and insightful feedback profoundly shaped this work at every stage.

My heartfelt thanks extend to my dear friend Eyuel and my branch manager Tsega for their steadfast companionship and support, which provided continuous motivation during challenging moments of this endeavor.

Finally, I acknowledge with sincere gratitude all those who contributed to this achievement - my family, colleagues, and the institutions whose support, whether direct or indirect, made this academic milestone possible.

Table of Contents

List of Contents	Pages
Acknowledgements.....	i
Table of Contents.....	ii
List of Figures.....	v
List of Tables.....	vi
List of abbreviations.....	vii
Abstract.....	viii
CHAPTER ONE.....	1
1. Introduction.....	1
1.1 Background.....	1
1.2 Statement of the problem.....	2
1.3 Research Question.....	6
1.4 Objective.....	6
1.5 Scope of the study.....	6
1.6 Significance of the study.....	6
CHAPTER TWO.....	7
2. Literature Review.....	7
2.1 Introduction.....	7
2.2 Theoretical Review.....	7
2.2.1 Introduction to Climate Change and Agriculture.....	7
2.2.2 Cause for lack of productivity in Ethiopia.....	7
2.2.3 Methods of Climate Adaptation.....	9
2.2.4 System dynamics and agricultural modeling.....	10
2.2.5 Climate change variables' impact on agriculture.....	10
2.2.6 Contribution of agriculture to greenhouse emission.....	10
2.3 Review of Empirical Studies.....	11
2.4 Research gap.....	13
2.5 Conceptual Framework.....	13

CHAPTER THREE	15
Methodology	15
3.1 Methods of the study.....	15
3.1.1 Data nature and source	15
3.1.2 Dynamic Hypothesis	16
3.1.3 Causal Loop Diagram.....	17
3.1.3.1 Balancing and Reinforcing Loops	18
3.1.4 Stock and Flow Diagram (SFD).....	18
3.1.4.1 Definitions of the selected main variables of the model	22
3.1.5 Methods of Analysis.....	23
3.1.6 Possible Scenarios	23
CHAPTER FOUR.....	25
Result presentation and discussion	25
4.1 Descriptive result and analysis.....	25
4.2 Model Structure Validity Test	25
4.2.1. Structure verification test.....	25
4.2.2. Parameter verification test.....	26
4.2.3. Extreme condition test.....	26
4.2.4. Boundary adequacy test.....	28
4.2.5. Dimensional consistency test.....	28
4.3. Model behavior test.....	29
4.3.1 Behavior reproduction test.....	30
4.3.2. Behavior Sensitivity test.....	30
4.4. Scenario design	33
4.4.1 Scenario 1: Adoption of drought-resistant crop varieties and improved seed.....	33
4.4.2 Scenario 2 Expansion of irrigation	34
4.4.3 Scenario 3 Organic Fertilizer Use	34
4.4.4 Scenario 4: Combination of all policy scenarios	35
4.5 Scenario analysis.....	35
4.5.1 Base Case.....	35
4.5.2 Policy of improved seed implemented	37

4.5.3 Policy of expansion of irrigation Implemented	38
4.5.4 Policy of organic fertilizer use Implemented	39
4.5.5 Combination of all policy scenarios	41
CHAPTER FIVE.....	44
5. Conclusion and policy recommendation	44
5.1 Conclusion.....	44
5.2 Policy Recommendations.....	45
References	47
1. Appendix A: Model equations, values and units.....	50
2 Appendix B Historical data	60

List of Figures

Figure 1: Conceptual framework of the study	14
Figure 2: A causal loop diagrams	17
Figure 3: Stock and flow diagram.....	20
Figure 4: Simulation results for crop production under extreme tests of productivity.....	27
Figure 5: Simulation results for chemical fertilizer emission under extreme tests of average chemical fertilizer emission.	28
Figure 6: Behavioral reproduction test for selected variables	30
Figure 7: Sensitivity analysis for a share of improved seed	31
Figure 8: Sensitivity analysis for a share of the irrigation rate	32
Figure 9: Sensitivity analysis for a share of fertilizer use.....	33
Figure 10: Simulated values of crop production, cultivated land, livestock and greenhouse gas concentrations (GHG) under base case.....	36
Figure 11: Comparison of improved seed policy and base run scenario	37
Figure 12: Comparison of irrigation policy and base run scenario	39
Figure 13: Comparison of substitute 50% of chemical fertilizer and base run scenario	40
Figure 14: Comparison of all policy scenarios	41
Figure 15: GHG concentration from 2000 to 2050 with projection under different scenario.	42
Figure 16: Total crop production from 2000 to 2050 with projection under different scenario..	43

List of Tables

Table 1: Initial value and values for selected parameters of the model.....	21
Table 2: Dimensional consistency test for selected stock, flow and auxiliary variables.	29
Table 3: GHG concentration from 2000 to 2050 with projection under different scenario.....	42
Table 4: Total crop production from 2000 to 2050 with projection under different scenario.	42

List of abbreviations

AGP:	Agricultural Growth Program
CLD:	Causal Loop Diagram
CRGE:	Climate-Resilient Green Economy (Ethiopia)
CSA:	Climate-Smart Agriculture
FAO:	Food and Agriculture Organization
GDP:	Gross Domestic Product
GHG:	Greenhouse Gas
IFPRI:	International Food Policy Research Institute
IPCC:	Intergovernmental Panel on Climate Change
LT-LEDS:	Long-Term Low Emission Development Strategy
MoA:	Ministry of Agriculture (Ethiopia)
MoWE:	Ministry of Water and Energy (Ethiopia)
NMA:	National Meteorological Agency (Ethiopia)
SD:	System Dynamics
SDGs:	Sustainable Development Goals
SFD:	Stock and Flow Diagram
TLU:	Tropical Livestock Unit
UNEP:	United Nations Environment Programme
USAID:	United States Agency for International Development
WFP:	World Food Programme

Abstract

Ethiopia's agriculture for livelihoods and economy is extremely vulnerable to climate change by the increasing temperature, irregular rainfall, and land degradation. Here, a system dynamics model was employed to evaluate the long-term impacts of climate adaptation policies on major crop production and greenhouse gas (GHG) emissions in Ethiopia. Using the Ministry of Planning, World Bank and Central Statistical Agency (2000-2020) data, the model simulates four policy scenarios between 2000 and 2050: (1) adoption of improved seeds and drought-resistant crops, (2) expansion of irrigation, (3) substitution with organic fertilizer, and (4) combined approach. Results indicate productivity versus sustainability trade-offs, more seeds increase output without land increases, reducing GHG emissions; irrigation increases production but raises emissions by a large magnitude; organic fertilizer reduces emissions but lowers small yield gains. The triple policy produces the highest crop output (131,086 metric tons in 2050) in a stable emissions scenario. We conclude that indicators of integrated adaptation strategies Improved seeds, sustainable irrigation, and organic fertilizers combined need to be implemented to guarantee adaptation for secure and sustainable agriculture. Recommendations include the increase of improved seed availability, promotion of solar irrigation, transition towards organic soil management, and enhancing institutional coordination and farmer support.

Keywords: *Climate adaptation, system dynamics, crop production, Ethiopia, sustainability.*

CHAPTER ONE

1. Introduction

1.1 Background

Food security and agricultural productivity are facing serious challenges due to climate change. Agriculture's capacity to feed the most vulnerable could be severely exposed by the anticipated effects of climate change, which include higher temperatures, more frequent extreme weather events, water shortages, rising sea levels, ocean acidification, land degradation, ecosystem disruption, and biodiversity loss. This would impede efforts to eradicate hunger, malnutrition, and poverty. (FAO, 2016).

Concerns over the current future of global agricultural productivity have grown throughout time. In poorer nations, where the majority of farmers still employ backward farming equipment, this anxiety is especially acute. The current concern stems from the possibility that depleting agricultural output may not be sufficient to feed the world's population, which could have serious implications for global food security. Climate change has been identified as one of the causes contributing to the decline in agricultural productivity. Not only do changes in climate affect agricultural output, but they also endanger human survival. (Ekpenyongudom oh)

Ethiopia's economy is mostly reliant on agriculture, which employs 75% of the workforce, generates 80% of exports, and accounts for 40% of GDP. However, crop yields from small farms fall short of regional averages, and just 5% of the land is irrigated. The use of better seeds, fertilizers, and insecticides is still restricted, and market connections are minimal. Despite these obstacles, Ethiopia's persistent poverty and food insecurity may be permanently resolved through agriculture-led economic growth that is connected to better livelihoods and nutrition. (USAID, 2020).

Our economic growth and the livelihoods of our people are highly affected by current weather variability. These impacts could get worse with climate change. By 2050, the negative impact of climate change, under an extreme scenario of higher temperatures and increased intensity and frequency of climate change, under an extreme event, could cost Ethiopia 10% or more of its GDP. Due to drought, floods, and soil erosion. The worst impacts are caused by drought. (CRS)

The country's adaptive capacity is constrained by limited livelihood options for the majority of the population, inadequate ability to withstand or absorb disasters, and the prevailing biophysical shocks it faces, according to Ethiopia's 2019 National Adaptation Plan. Stronger climate adaptation policies, programs, and implementation capabilities across sectors, intervention levels, and actors are required to address these issues (MoA, 2015; MoWE, 2015).

Climate change is having an impact on Ethiopia. In addition to the immediate consequences, such rising average temperatures or altered rainfall patterns, climate change also offers the chance and need to transition to a new, sustainable development paradigm. Therefore, in order to safeguard the nation from the negative consequences of climate change and to create a green economy that will support the country's goal of becoming middle-income by 2025, the Federal Democratic Republic of Ethiopia's government launched the climate-resilient green economy (CRGE) initiative. (CRGE, 2011).

The growing interest in researching the interactions among population dynamics, climate change, land productivity, and climate adaptation methods is crucial for addressing agricultural challenges. Previous studies have identified various causes of insufficient agricultural production, including erratic rainfall, land degradation, imperfect markets, and rapid population growth (Melaku,2013). An integrated approach, such as system dynamics, allows for a comprehensive examination of these complex interactions. However, this sector remains one of the least researched in emerging economies (Akram, 2013). Therefore, it is more important than ever to conduct targeted research to address the associated environmental issues (Gerber et al., 2013). Ultimately, creating a sustainable environment is essential for ensuring sustained social and economic progress (Mishra, 2020; United Nations Environment Program) (UNEP, 2015).

1.2 Statement of the problem

Climate change is one of the world's challenges in the 21st century that affects the environment, food security, economies, and human well-being. The Intergovernmental Panel on climate change (IPCC AR6, 2023) report shows that 3.3 to 3.6 billion people of the world live in regions that are highly impacted by climate change. From those areas, sub-Saharan Africa is the most highly affected area, a region that heavily depends on agricultural activity for both livelihoods and the national economy. This dependency is exposed to climate-related shocks such as temperatures, variable precipitation, and increasing frequency and intensity of extreme weather

events. Ethiopia, as one of the largest and most populous countries in the region, is emblematic of these challenges.

In Ethiopia, agriculture is the back bone of the economy, employing 75% of the population and contribution of 40% to the country's GDP not only this it also vital for food security, rural livelihoods, and poverty reduction (Yesuf et al, 2008). However, mainly depends on rain-fed with only 5% of the potential irrigable land (Yesuf et al., 2008). According to National meteorological agency (NMA, 2020), the country has experienced a rise in 1.2 degree Celsius in average for the last 50 years, along with a 15 to 20% decline in annual rainfall in several regions. These climate changes have resulted from drought frequency, erratic rainfall, and soil degradation. In 2022 alone, more than 20 million people required emergency food aid due to climate-induced droughts (WFP, 2022).

The highest decline of any region has been in Africa, where climate change has already slowed the growth of agricultural productivity by an estimated 34% since 1961 (IPCC, 2023). Ethiopia is a prime example of this weakness. One of the worst droughts in decades struck the Horn of Africa in 2021–2022, decimating cattle and crops over large swaths of land (FAO, 2023). Because of this, agricultural production has stalled, and under changing climatic conditions, staple crop yields are trending downward even in years without drought (Feleke et al., 2025). Future prospects are dire if adaptive steps are not taken. According to a recent economy-wide simulation, chronic climate change may cause yields of Ethiopia's main crops—teff, maize, and sorghum—to drop by more than 20% by the middle of the century, which would result in a decline in GDP and exports.

The consequences of these climatic shifts are especially evident in declining agricultural productivity, particularly crop production, which constitutes the largest share of agricultural GDP. Crops such as teff, wheat, maize, barley, and sorghum are the main food sources for millions of Ethiopian households. Average yields of crop in Ethiopia approximately 2.1 tons per hectare significantly below the global average 4 tons per hectare (FAO, 2020). This stagnation in crop productivity is the effect of climate variability, soil degradation, low input use, and limited adoption of technology.

The climate resilient green economy (CRGE) strategy launched in 2011, efforts to increase crop productivity have been hampered by multiple structural and environmental constraints. The

CRGE aims to achieve middle income status by 2030 while reducing GHG emissions 250Mt CO₂ compared to business as usual conditions. However, the reality on the ground reveals that climate change continues to outpace adaptation efforts.

Most of the farmers are particularly vulnerable due to limited climate information awareness, limited access to credit, modern technology, and extension services (IFPRI, 2018). These limitations are highly affected their capacity to adopt climate smart agriculture practice.

The economic outcome of crop productivity is highly declined due to climate changes are highly concerning area. (Solomon et al, 2021) CGE model to project the economy wide impact of climate change on Ethiopian agriculture. Major crops such as teff, maize, and sorghum are expected to decline by 25.4%, 21.8%, and 25.2% respectively. Additionally, the overall GDP at market prices could drop by 28.9%, and exports may fall by as much as 35.7%. The study also highlights that poor rural households will be disproportionately affected, experiencing the declines in income and consumption.

According Mohammed (2020) and Wubic (2015), unseasonal rains, delayed planting seasons, and prolonged dry spells have lead to seed rot and widespread crop yield losses. In moisture sensitive areas extended dry seasons have highly reduced soil moisture and fertility of the soil, while lowland regions face intensified heatwaves and high evapotranspiration rates. A study based on the Nile Basin farmers survey studied by yesuf et al. (2008), showed that 62% of respondents observed a decline in rainfall and 68% increasing temperature over two decades and 58% of these farmers did not take any adaptive measures, largely due to financial constraints, lack of knowledge, and absence of institutional support.

Climate change impacts on crop yields vary in vulnerability and adaptive capacity from one region of the nation to another. Lowland pastoral and high land dryland areas risk vulnerability to high temperature variability and water shortage from high temperature and kassahun Abera (2011) explained that in this kind of region the variability of the rain degrades the use of fertilizer effectiveness and crop yield particularly cereals. Land extensification has remained the predominant means of improving agriculture production. However, it has remained an unsustainable one owing to land degradation, deforestation, and increased competition for scarce natural resources.

The recent works of Berhane (2018), Gebrechorkos et al. (2019), Abegaz et al. (2024), Zerayehu, Tsegaye and Dawit (2020) employed time series and cross sectional data. First, most of the previous studies utilizing time series and cross sectional data were unable to capture the dynamic interrelationships between climate variables, agriculture systems and socio-economic conditions. Second the majority of the studies focused on a single adaptation option like use of drought resistant crop, use of irrigation system, climate smart agriculture and use of improved seed without taking into account their tradeoffs. Third institutional and policy contexts of importance in facilitating or constraining adaptation remain ignored. Lastly few studies break down climate impacts and adaptation responses by agro-ecological zones.

To these intricate challenges, a system based analysis has to be employed to capture inter-relatedness and feedbacks within the Ethiopia climate adaptation and production system. The paper wishes to utilize a system dynamic modeling (SDM) approach in order to investigate complex inter-relationships between climate variables, adaptation alternatives, institutional setting and production. Unlike the classical normal linear model SDM allow the simulation of non-linear association, time delay and feedback mechanism this lead to long term effect and efficient adaptation alternatives and tradeoff among them.

This study makes several contributions to policy makers and researchers. First by presenting SDM models considering diverse agro-ecological zones, socio-economic diversity and institutional capacity. Second by considering variables such as policy coherence, access to climate information and financial services in the rural area. Third by enabling simulation of different policy scenarios, CSA, irrigation system, technology uptake and use of improved seeds as major drivers of adaptive capacity and identify leverage points.

Through a systems and integrated perspective, this study aims to enhance the link between evidence and policy making. The study aims to provide evidence to inform agriculture resilience enhancement and safeguarding of rural live livelihood and inform Ethiopia's development agendas like the CRGE and the SDGs. Overall, study results will be expected to form the evidence basis of policy making, inform the decisions on resource allocation and help in sustainable and inclusive agriculture development in the face of increasingly rapid climate change.

1.3 Research Question

The study used a system dynamics modelling method in analyzing the interaction between agricultural productivity and climate adaptation. The study was guided by the following questions;

- What are the drivers of agricultural productivity in the context of climate change?
- How do climate variables influence crop production?
- What are the most effective adaptation measures to enhance agricultural productivity?

1.4 Objective

The study's primary objective is to develop a dynamic model that evaluates the interaction between climate adaptation, such as improved irrigation systems, drought-resistant crops, climate-smart agriculture, agroforestry, and agricultural productivity. In addition to the primary objective the model aims to;

- Identify key drivers of agricultural productivity in the context of climate change.
- Analyze the relationship between climate variables and agricultural productivity.
- Evaluate the effectiveness of various adaptation strategies.

1.5 Scope of the study

The study is geographically confined to Ethiopia. It has particular interest in climatic drivers of change like rainfall, drought, flooding, temperature, and soil erosion. Conceptually, the study was concerned with the relationships between climatic drivers and farm productivity and the contribution of the sector to greenhouse gas emissions. System dynamics modeling will be applied in the methodology of the study to analyze the dynamics and complexity of the relationship between agriculture production and the key crops and climate change.

1.6 Significance of the study

The study contributes to the ongoing national policy on the environment, agriculture and climate adaptation plan to achieve efficient agricultural productivity in the sector with climate smart manner. The study support farmers, agriculture, employment of the sector, and other stockholders regarding the environment effect and productivity of the sector. Finally, it informs that sensitive adaptation options for better management practices to create an efficient agriculture production system that promotes output and socioeconomic growth in a climate-smart manner.

CHAPTER TWO

2. Literature Review

2.1 Introduction

This chapter focuses on reviewing the literature in the area of agricultural sector specifically in major crop production. Theoretical and empirical literature review was discussed and also an overview of the crop production and greenhouse gas emission at country level. The theoretical and empirical framework helps to understand the current state of knowledge on the research and scholars view towards the title of the research and gaps of research. Finally, the conceptual framework is developed from those.

2.2 Theoretical Review

2.2.1 Introduction to Climate Change and Agriculture

Ethiopia is affected by the global phenomena of climate change, which also has an impact on the environment, society, and agriculture. A large portion of Ethiopia's population makes agriculture their main source of income, and the country's economy is largely dependent on it. Rising temperatures, more temperature variability, altered precipitation levels and frequency, more frequent dry spells and droughts, more intense extreme weather events, rising sea levels, and the salinization of freshwater and arable land are already having a negative impact on agricultural production in many areas. It will get harder to manage forests, rear livestock, grow crops, and catch fish in the same methods and locations as we did in the past as the effects of climate change on agriculture worsen. (FAO, 2016)

2.2.2 Cause for lack of productivity in Ethiopia

2.2.2.1 Drought

Drought constitutes one of the greatest production limiting factors to agriculture in Ethiopia. The country has been hit by frequent bouts of droughts and climate change, which adds to crop and livestock losses as well as food insecurity. The frequency and intensity of the droughts enhance in East Africa by the IPCC (2023). The frequency and intensity of the droughts will contribute to the vulnerability of the agriculture production in Ethiopia. (Herrera & Kopainsky, 2020)

2.2.2.2 Rainfall

Potential water scarcity restraints and consequent agriculture sector-based conflict pose challenges in the context of global warming. Melaku, M. (2013), LT-LEDS, 2020-2050; Sabine, E. et al., 2023). Much of the precipitation goes to waste as a result of inefficient conservation and poorly designed water harvesting facilities, even though output depends on precipitation and redistribution.

A mere 1% of an estimated 110 billion cubic meters of the total surface water provided annually goes into hydropower and irrigation (Chadhokar, A.P., 2003 Proceedings of the Food Security Conference, p.139).

2.2.2.3 Land degradation

The remaining 20 non-agriculture emissions are almost entirely the result of land use, i.e., deforestation and land degradation. Deforestation and land degradation continue to take place due to the continued yearly loss of carbon stock in biomass, even though emission increase due to land has dwindled remarkably since approximately 2007. Poor and low pasture quality, drought, and soil degradation are among Ethiopia's most critical production constraints (Birhan & Adugna, 2014). Forage production is reduced by drought and Sahel rangeland degradation (FAO, 2016).

2.2.2.4 Low input

The use of agricultural inputs, such as improved seeds, fertilizers, and pesticides, remains low in Ethiopia due to limited access and affordability for smallholder farmers. Many farmers rely on traditional farming methods and low-quality seeds, which result in poor crop yields. The lack of access to modern agricultural technologies and extension services further limits productivity. For example, only 10% of Ethiopian farmers use improved seeds, and fertilizer application rates are among the lowest in Sub-Saharan Africa (USAID, 2020).

2.2.2.5 Temperature

Rising temperatures due to climate change have a direct impact on crop growth and livestock health. Higher temperatures accelerate evapotranspiration, reduce soil moisture, and increase heat stress on crops and animals. In Ethiopia, temperatures are projected to rise by 1.5–2°C by

2050, which could reduce yields of staple crops like maize, wheat, and teff by 10–20% (Rahel et al., 2021). Extreme heat events also increase the risk of crop failure and livestock mortality.

2.2.2.6 Soil Health, Nutrient levels and Erosion rates

Soil health is a critical determinant of agricultural productivity. In Ethiopia, soil degradation due to erosion, nutrient depletion, and salinization has severely impacted soil fertility. Poor soil health reduces the availability of essential nutrients for crops, leading to lower yields. Conservation agriculture practices, such as crop rotation, mulching, and reduced tillage, have been shown to improve soil health and productivity (Ibsa & Feysel, 2021) and Nutrient levels in Ethiopian soils are often inadequate due to continuous cropping without adequate fertilization. Soil moisture content is highly variable, with dry spells and droughts reducing water availability for crops. Soil erosion rates are among the highest in the world, with an estimated 1.5 billion tons of soil lost annually due to water erosion (FAO, 2016). These factors collectively contribute to low agricultural productivity.

2.2.2.7 Technology

The adoption of modern agricultural technologies, such as improved seeds, irrigation systems, and mechanization, is limited in Ethiopia. Smallholder farmers often lack access to these technologies due to financial constraints and inadequate extension services. The limited use of technology restricts farmers' ability to adapt to climate change and improve productivity. For example, only 5% of agricultural land in Ethiopia is irrigated, compared to 37% in North Africa (USAID, 2020).

2.2.3 Methods of Climate Adaptation

Ethiopia has encouraged several climate adaptation options to reduce the effects of climate change on agriculture. They consist of encouraging drought-tolerant crops, enhancing water management, and soil conservation practices. Climate-smart agriculture (CSA) is an integrated approach to improve productivity, resilience, and sustainability. Examples are agroforestry, conservation agriculture, and integrated soil fertility management, which have been extensively promoted. The success of such options, however, depends upon farmers' access to information, institutions, and resources.

2.2.4 System dynamics and agricultural modeling

System dynamics (SD) is a powerful tool for modeling complex systems, such as agricultural production, by capturing feedback loops, delays, and non-linear relationships. SD has been used to analyze the interactions between climate variables, agricultural practices, and productivity outcomes. For example, Bala et al. (2017) used SD to model the impacts of climate change on crop yields in Sub-Saharan Africa. In Ethiopia, SD can help policymakers evaluate the long-term effects of adaptation strategies and identify leverage points for improving agricultural resilience.

2.2.5 Climate change variables' impact on agriculture

Due to increased frequency and magnitude of droughts, Ethiopia's agriculture sector remains extremely climate change-exposed. Ethiopia's agriculture sector is extremely climate change-exposed as a result of increased frequency and intensity of droughts. The sector has a low capacity to adapt to the impacts of climate change. LT-LEDS analysis of agriculture and climate change takes into account the effect of water scarcity resulting from precipitation variability on yields. (2020-2050 LT-LEDS)

Greenhouse gas emission affects marketed and non-traded crops like teff, maize, and wheat where some activities in the production process of the agriculture sector come into consideration. Under the influence of CRGE, the production of teff decreases from 10.53 billion Birr to 9.88 billion Birr by 2030 when compared with 9.69 billion Birr without the influence of CRGE. This articulates that the decrease in productivity in agriculture factors in terms of greenhouse gas emission results in a 7.9% decreased production of teff without the influence of CRGE. The effect of the emission of CO₂ on the production of teff decreases to 6.1% under the influence of CRGE. The reduction in the productivity of agriculture factors in terms of greenhouse gas emission has even worse impacts on increasing production in maize and wheat production in either case, which articulates that the responsiveness of agriculture activities varies with the behavior of the producer. (Zerayehu, Tsegaye, and Dawit, 2020)

2.2.6 Contribution of agriculture to greenhouse emission

Agriculture is one of the major sources of greenhouse (GHG) emission in Ethiopia in terms of agriculture soil management, livestock production, and deforestation. Agriculture contributes

21% to national GHG emission (FAO, 2016). The major drivers of these emission activities are methane from husbandry and fertilizer-induced nitrous oxide. GHG emission reduction in agriculture will contribute heavily in achieving Ethiopia's Climate-Resilient Green Economy (CRGE) targets.

2.3 Review of Empirical Studies

Several studies have considered the challenges and opportunities in the agricultural sector, and described its significant contribution to economic development, social health, national growth, and food security. Nevertheless, the sector is significantly a source of greenhouse gas emissions directly and indirectly. Climate change is one and a severe global issue that affects agriculture, water supply, market conditions and natural resources. This sector is fundamentally complex and sensitive sector, and in the sector technology playing crucial roles in determining productivity and profitability (Berhane, 2018).

The second highest emitter, following the energy sector, is agriculture (Asmamaw & Mingyong, 2024). Ethiopian crop production depends mostly on rainfall for moisture, with irrigation covering merely 1.1% of the nation's cultivatable land. Rainfall amount and distribution are of critical importance to successful crop production.

The majority of the agricultural land is in the highlands (above 1500 meters), where 44% of the total area is cultivated, 95% of the available arable land is cultivated, and about 90% of the total population lives. The area, nevertheless, has some key issues, such as the loss of vegetative cover. It has been estimated that about 59,000 hectares of forest are cleared for agricultural land annually in three big forest areas of Ethiopia (WBISP Project, 2004). Land susceptibility, compounded by steep relief and poor farming practices, has led to unprecedented soil loss (Keyzer et al., 2001; Amede et al., 2001; Zelleke et al., 2010).

Attempts at valuing land degradation in Ethiopia have shown significant economic effects through production loss and yield reduction (Yesuf et al., 2005). Land degradation reduces agriculture by about 7% of its value annually, as attested by Jolejole-Forman (2012). In addition to fertility loss and economic loss, land degradation influences farmers' livelihood through water quality and biodiversity. There has also been internal migration among some of the farmers

because of the decreasing fertility of their soils, which can no longer sustain their livelihood (Sonneveld et al., 2002).

The low productivity in agriculture could be a reflection of hidden fertility problems in Ethiopia. The national mean maize yield during the 2008/09 season, for example, was just 2.2 tons per hectare, which is far below the potential maize yield of 4.7 tons per hectare exhibited in farm trials (Awlachew et al., 2010). Besides, fertilizer utilization efficiency has not been as expected; maize's nitrogen use efficiency (NUE) in Ethiopia is between 9 and 17 kg of grain per unit of nitrogen applied, whereas in Kenya it is between 7 and 36 and in Tanzania between 18 and 43 (Zelleke et al., 2010).

Recent years have witnessed empirical studies employing different modeling approaches in a bid to evaluate the Sub-Saharan Africa's climate change effects and adaptation measures. To investigate trends in the Horn of Africa, Gebrechorkos et al. (2019) for example employed high-resolution climate models and crop yield simulations. From their study, it was established that maize and sorghum yields were significantly affected by rainfall variability and rising temperatures. Their model's policy usefulness was thus shortened by not controlling for feedback effects or socio-institutional adaptation pathways. In the same way, Abegaz et al. (2024) evaluated Ethiopian adoption of climate-smart agricultural practices from cross-sectional survey data. Though it identified improved food security and resilience, it also identified that adoption was heavily influenced by access to extension services, credit, and land tenure security adoption drivers hardly modeled.

Additionally, 2020's Zerayehu, Tsegaye, and Dawit applied a computable general equilibrium (CGE) model to simulate the economic effects of greenhouse gas emissions on the agricultural sector in Ethiopia. Their high-emission scenario projections of yield losses for crops were significant most so for teff, wheat, and maize. While powerful in their ability to capture market interdependencies, CGE models assume stationary behavioral responses and do not incorporate nonlinearities or dynamic feedbacks over time. This methodological limitation highlights system dynamics models' ability to represent delayed effects and balance/reinforcing loops.

A second recent paper by Abegaz et al. (2023) employed four agro-ecological zone panel data to evaluate the determinants of smallholder farmers' adaptive capacity. The authors found that

although adoption of more than one adaptation strategy (e.g., improved seed, soil conservation, irrigation) resulted in productivity increases, the majority of farmers did not have institutional support for maintaining change. Interestingly, the research did not cover how adaptation options compete or interact under conditions of limited resources one of the areas where system-based modeling offers greater insight.

2.4 Research gap

According to the empirical literature, several studies looked at various connection between climate change and crop production. While these studies provide valuable evidence, many are limited in scope, treating adaptation as a set of independent interventions and failing to explore the synergistic or conflicting impacts of their combined implementation. Additionally, spatial and agro-ecological variation is often underrepresented, and behavioral dynamics such as learning, feedback, and institutional evolution are frequently omitted. This paper contributes to the literature by employing a system dynamics approach that explicitly models these complex interactions, enabling policymakers to explore multiple adaptation scenarios over time and better understand long-term trade-offs and leverage points for action.

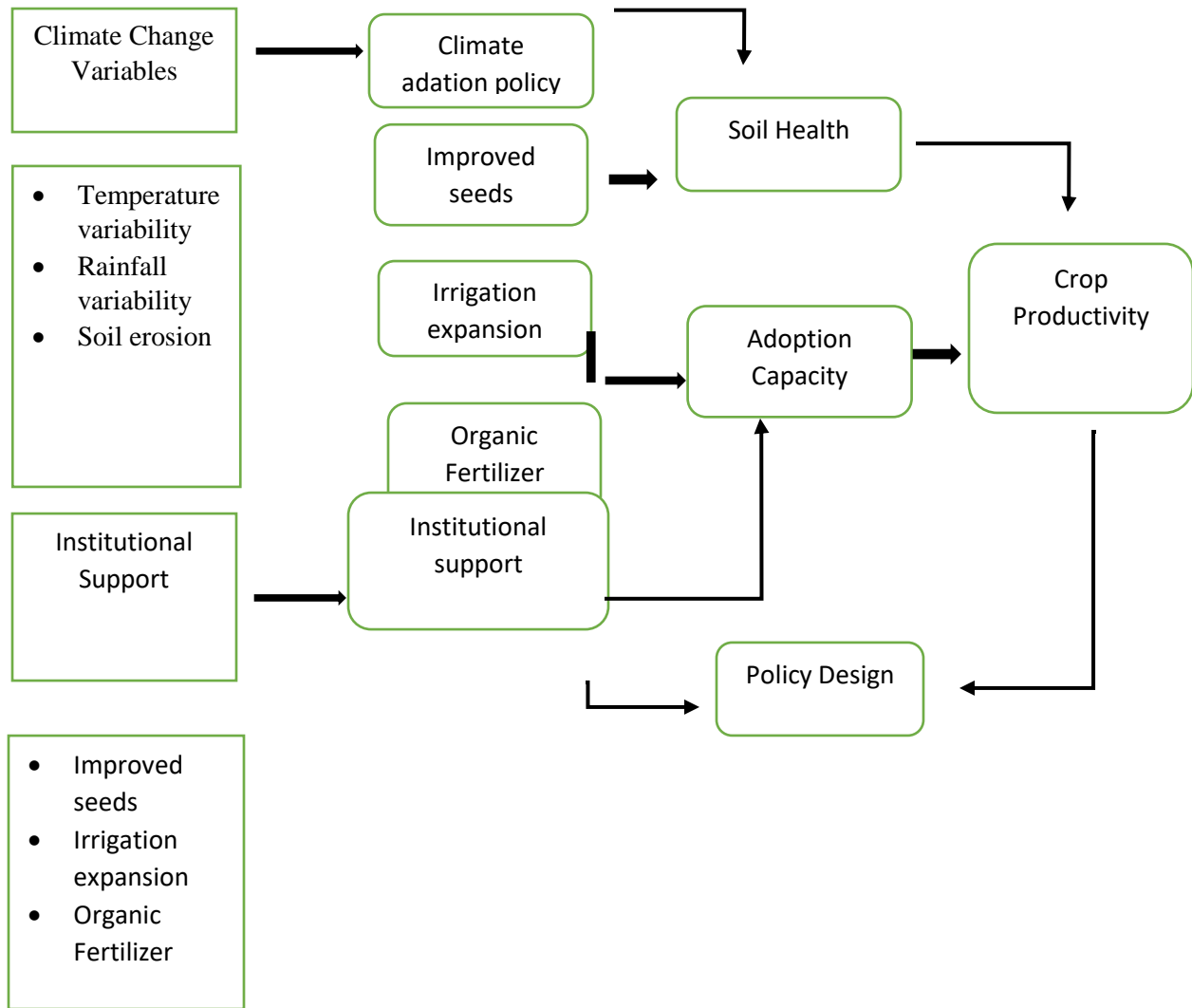
2.5 Conceptual Framework

The conceptual model shows how certain adaptation practices and external climatic e lead to agronomic as well as environmental effects. Climatic variability of temperature, variability of rainfall, and erosion of soil are the major drivers of adaptation at the left edge. All of these drivers facilitate a range of climate adaptation strategies (e.g., increased irrigation facilities, quality seeds, and use of organic fertilizer) with two intermediary effects: soil health and adoption capacity in communities. Improved seed quality and organic fertilizer have direct impacts on soil health, but the capacity to adopt is influenced as well by institutional support networks, fertilizer use, and the presence of irrigation. Crop productivity is affected by a variety of processes at the field level.

In addition to this direct chain of influence, the design incorporates a feedback mechanism so that shifts in crop productivity influence rural livelihoods and greenhouse gas (GHG) emission patterns, and these inform policy design. In addition to increasing adoption capacity, institutional support loops empirical data on productivity and emission impacts back into the policymaking

process, allowing adaptation strategies to be gradually improved. The model thus captures the causal pathways from climate distress to productivity in a forward direction and the reverse loop whereby realized socio-economic and environmental effects feedback into successive iterations of policy choice.

Figure 1 conceptual framework of the study



Source: Own computation

CHAPTER THREE

Methodology

3.1 Methods of the study

Most of the issues being faced at present like the use up of natural resources, global warming, and productivity in agriculture are the unintended or unplanned outcomes of past action or intervention. A systemic approach that can deal with the dynamic complexity of the issue is therefore required.

The new method known as system dynamics is applied to comprehend real-life complicated issues over time as a foundation for making decisions that result in long-term sustainability. The new method was discovered in the 1950s by Jay Forrester and was initially applied in economic cycle analysis on the industrial front (Forrester, 1961). Ever since, it has been used to model issues in numerous areas of economic, social, and environmental research. For example, Ford (2010) provides examples of how system dynamics can be utilized to model environmental issues in his book. It was utilized by Forrester (1969) and Forrester (1971) to model socioeconomic dynamics.

3.1.1 Data nature and source

The study employs a system dynamics approach to analyze the feedback dynamics and non-linear interactions between climate variable dynamics, crop production dynamics, climate adaptation mechanisms and GHG emissions. The system dynamics method is best placed to model the complexities of these interactions because it is possible to model balancing and reinforcing feedback loops that influence agricultural productivity and economic progress with the passage of time. Through this approach, causal loop models and stock-flow simulations will be developed to simulate the effects of various policy interventions on crop production performance. In modeling the dynamics of these processes, the study employs elasticity functions to capture non-linear relationships between most of the key variables.

For example, the elasticity estimates from empirical evidence will capture crop production responsiveness to rainfall variability changes, technological take-up, fertilizer use, conservation mechanism in the soil and irrigation. Such functions will make the model reflect realistic system behaviors like threshold effects as well as diminishing returns that are needed to describe the feedback dynamics in the crop production. The estimates are based on precise data collected

from the Ministry of Planning and the Central Statistical Agency (CSA) of Ethiopia. The most important data sets utilized are population projections, agriculture production, and. Data sets serve as the foundation for estimating values such as the growth rates of population, participation rates in the labor force, sectorial employment elasticity's, and economic outputs. The study also uses qualitative data from policy reports and documents to place the quantitative results into context in the broader policy environment. The model was calibrated and validated using historical data to ensure the reliability of the simulation. Sensitivity analysis will be employed to evaluate the alteration of key parameters; such as crop production output. This technique will enable a credible ground on which to examine the long-term effects of policy intervention to ensure inclusive and sustainable economic growth.

By the use of system dynamics modeling and integration of diversified data sources, this research aims to provide in-depth understanding of the interdependencies between climate variable, climate adaptation mechanism and crop yield. The outcome will assist in informed decision-making in the mitigation of the dangers and opportunities in the agricultural productivity of Ethiopia in consideration of its overall development goals.

The model was operating for fifty years, i.e., between 2000 and 2050. The first 10 years were the pre-introduction years of the Climate Resilient Green Economy (CRGE). The subsequent 15 years, after the introduction of CRGE, would serve as a base model, and the last 25 years would simulate the future dynamics of the model.

3.1.2 Dynamic Hypothesis

The agricultural commodities market in Ethiopia is expanding over time due to population expansion, while productivity for these important crops like barley, wheat, maize, and sorghum is decreasing. This decline primarily is due to the agriculture sector's heavy reliance on the rain-fed system as well as a number of interacting factors like the uncertainty of weather, loss of land, declining soil fertility, drought, lack of technological advancement, and erosion. These stresses cause deforestation, which enhances climate impacts by decreasing the forest's capacity for CO₂ sequestration while simultaneously increasing CO₂ emissions from burning biomass.

By adopting the application of climate-smart agriculture, the utilization of irrigation systems, the use of natural fertilizers, seed quality improvement, and encouraging technology uptake and drought-resistant crops, agricultural productivity can be improved significantly. By tackling the

climatic factors affecting agricultural productivity and developing complex adaptation measures, we can enhance the productivity and resilience of agriculture in Ethiopia.

Moreover, the inclusion of education and community involvement in these strategies is crucial to their success. Educating farmers on sustainable practices and access to resources can make new methods more accessible, enhancing productivity. Collaborative efforts of government bodies, NGOs, and local communities can help ensure that the strategies are tailored based on the needs of different regions, maximizing effectiveness. By fostering a participatory process, we can create an agricultural system that is more robust and will not only resolve the current issues but also prepare for future climate uncertainties.

3.1.3 Causal Loop Diagram

Causal loop diagrams (CLD) form a central part of learning system dynamics, balancing loops attempt to stabilize systems by resisting changes and reinforcing loops bring about growth, increase the value and result in exponential growth in variables. The loops are dependent on each other for example irrigation enhancement (B2) may lead to improvement in soil health (R2), productivity (R3). The whole system functions on the cycle of feedback, i.e., one process's output is input for another variable, e.g., boosted productivity of farms leading to boosted investment in technology, which further improve productivity. The complex relationship explains the dynamic interaction with agricultural system and its response to the environment.

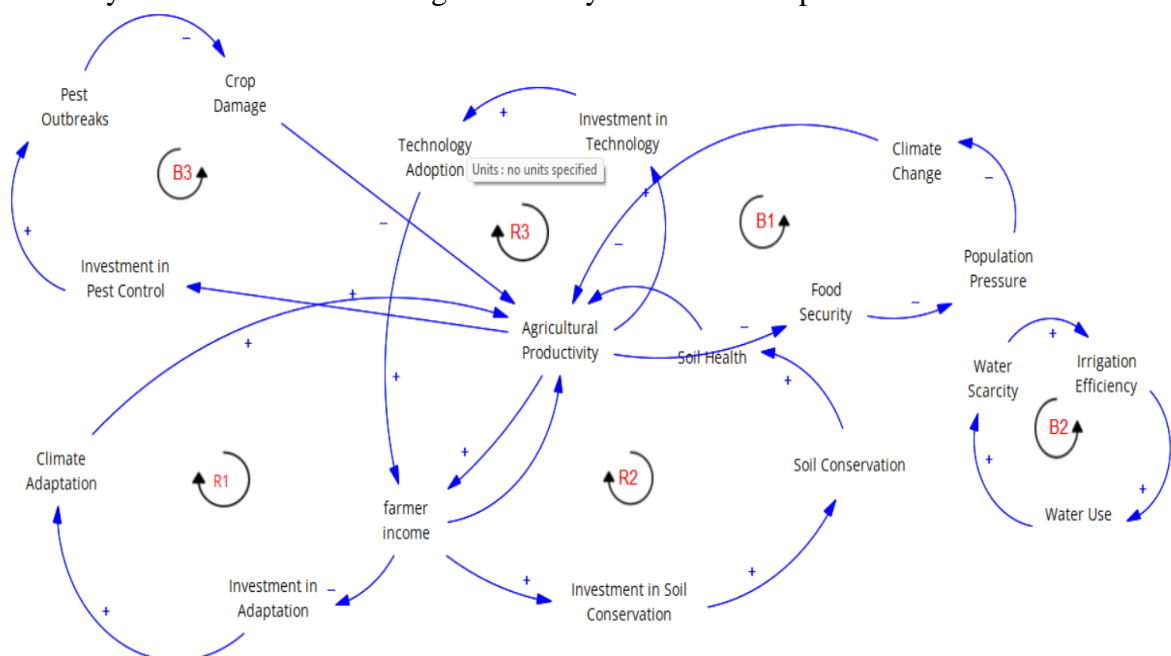


Figure 2 A causal loop diagrams

3.1.3.1 Balancing and Reinforcing Loops

The first reinforcing loop (R1) indicates farmers resort to different mechanisms in adapting with climate change in a bid to enhance productivity. The enhanced productivity gives rise to continuous improvement and encouragement to invest in climate adaptation.

Reinforcing loop (R2) describes how investment in soil conservation practice leads to healthier soil and sustains improvement in agriculture productivity. With agriculture productivity enhancement, investment in soil conservation practice will rise and reinforce the advantage of healthy soils.

Finally, reinforcing loop R3 addresses the interplay between technology investment and productivity in agriculture. Increased technology investment brings increased levels of productivity. The higher the level of productivity, the higher the level of technology investment and hence the reinforcing loop which creates escalating technological change in agriculture.

When we go to the balancing loop (B1) because increased productivity in agriculture increases food security. While increasing population pressure will translate into increasing food demand, which may impact the system and the resource of agriculture this generating the balancing effect in which levels are maintained in order to maintain food security.

Balancing loop (B2) deals with how water usage and the water use efficiency of the irrigation system relate to one another. An increased usage of water relates to increased irrigation practice. Increased irrigation efficiently prevents water scarcity and has the impact of balancing which enables an augmented sustainable agriculture water requirement.

Balancing loop B3 illustrates the impact of pest breakouts on crop damage. With increasing breakouts of pests, crop damage goes up and agriculture productivity declines. The farmers can react by spending on pest control, reducing damage and stabilizing productivity and creating a balancing dynamic.

3.1.4 Stock and Flow Diagram (SFD)

The stock and flow diagrams (SFD) convert causal loop diagrams (CLD) into quantified mathematical models, a critical step in converting mental models into understandable, communicable results. The SFD employs a differential system of equations to model the

reference behavior of the dynamic hypothesis. It is a network of feedback structures, illustrating finite difference equations along with feedback loop variables, representing the system dynamics over time (Sterman, 2000; Bala, Arshad, & Noh, 2017). The stock and flow diagram of the crop production system is illustrated in the figure below, illustrating the interrelationship between stocks and flows to define the behavior of the system.

Flows are the variables that cause stocks to build up or run down. The relationships between flow and stock variables are formulated in terms of integral or differential equations. A significant difference is that flow variables are in units per time, whereas stock variables are in units alone. To provide additional information, to symbolize external parameters, or to symbolize intermediate steps between stocks and flows, auxiliary variables are utilized (Martinez-Moyano & Richardson, 2013; J. D. Sterman, 2002). For our model's stock and flow diagram, there are four stock variables: population, livestock, GHG concentration, and cultivated land. Adequate literature informed the use of some algebraic and differential equations for the representation of feedback relations between stocks and flow variables (Homer & Hirsch, 2006).

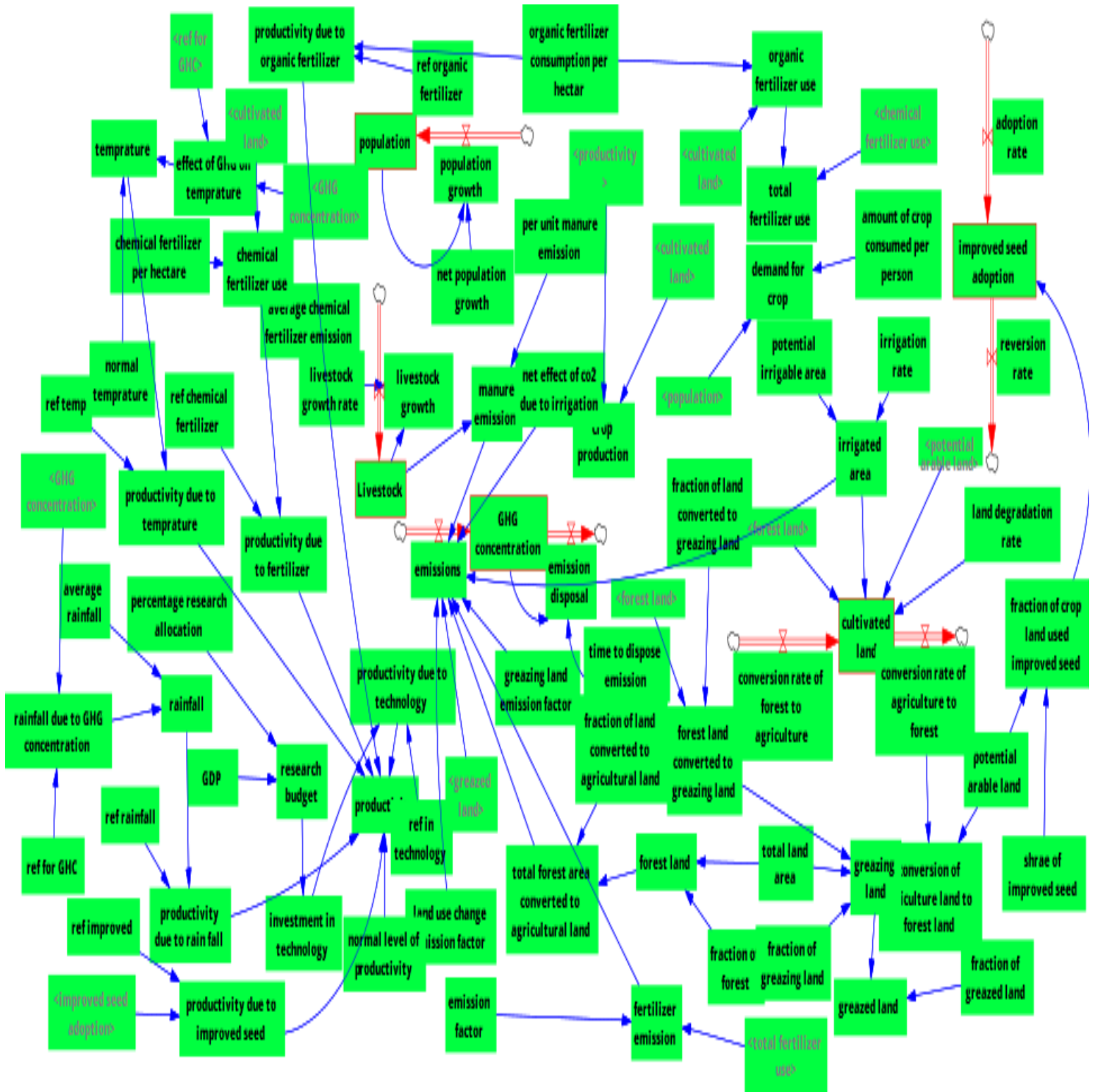


Figure 3 Stock and flow diagram

The stock-flow model needs the specification of equations and parameterization of variable and unit consistency before running the simulation. The table below provides a summary of variables with data source, unit of measurement and its value.

Table 1: Initial value and values for selected parameters of the model

Parameters	Initial value/value	unit	source
	67,031,867	person	United nation, department of economic and social affairs, population division (2024). world population prospects
Population growth rate	0.03	Dmnl/year	Population division (2024). World population prospects
Cultivated land	10,885,400	Hectar	FAO (2000) https://www.fao.org/4/x4358e/x4358e00.htm#P107_19830
GHG concentration	72,193,430,000	Kg Co2	World bank
average chemical fertilizer emission	2.6	Tonco2e/hectar/year	World bank <ahref='https://www.macrotrends.net/global-metrics/countries/eth/ethiopia/ghg-greenhouse-gas-emissions'>Ethio
Fertilizer consumption per hectare	7.59	Kg/hectare of arable land	World bank (2025)
Conversion rate of forest to agriculture	0.8	Dmnl/year	<u>World Development Indicators: 2003 - Page 131 (https://www.google.com.et/books/edition/World Development Indicators/UPb93-aQ1jAC?hl=en&gbpv=1&dq=RATE+OF+CROP+PRODUCTION+per+hectare+in+1990&pg=PA131&printsec=frontcover)</u>
Chemical fertilizer per hectare	0.152	Ton/hectare	Fertilizer supply chain in Ethiopia; structure, performance and policy analysis ((Agbahey et al.,

			2015)
adoption rate	0.03	1/year	https://en.wikipedia.org/wiki/Agriculture_in_Ethiopia
average rainfall	500	mm	Online library doi/10.1155/2022/4738416
conversion rate of agriculture to forest	0.07	1/year	FAO (2020). Global forest resource assessment. Rome; food and agriculture organization
conversion rate of forest to agriculture	0.0093	1/year	FAO (2020). Global forest resource assessment. Rome; food and agriculture organization
fraction of forest	0.122	DMNL	World Bank (2021).Ethiopia forest area
fraction of grazed land	0.23	DMNL	CSA (2019). Agricultural sample survey; livestock and livestock characteristics.
irrigation rate	0.1	DMNL	Awulachew,S.B.(2010). Irrigation potential in Ethiopia

3.1.4.1 Definitions of the selected main variables of the model

1. Crop production

Total crop production in metric ton is calculated as the product of cultivated land area (hectares) and land productivity (Ton/hectare). This variable represents the annual yield of major crops (e.g., teff, maize, wheat) under given climatic and policy conditions.

$$\text{Crop production} = \text{cultivated land} * \text{productivity}$$

2. Cultivated land

Cultivated land is the total land area (hectares) actively used for crop cultivation at a given time it dynamically changes positively due to irrigation, deforestation and negatively by degradation and reforestation.

$$\begin{aligned} \text{Cultivated land} = & \text{INTEG} (\text{irrigated area} + \text{conversion rate of agriculture} \\ & \text{to forest} * \text{forest land-potential arable land} * \text{conversion} \\ & \text{rate of forest to agriculture land degradation} \\ & \text{Rate} * \text{potential arable land, } 1.0885e+07) \end{aligned}$$

3. GHG concentration

It tracks the total greenhouse gases (measured in kg of CO₂-equivalent) accumulating from farming activities. This includes emissions from chemical fertilizers, livestock digestion, and when forests are converted to farmland. On the flip side, nature helps balance this through carbon absorption by plants and soils. The model calculates the net effect over time - what's emitted minus what gets absorbed - starting from an initial 36.6 million kg of CO₂e. Essentially, it shows how agricultural choices impact our atmosphere's heat-trapping gases year after year.

$$GHG\ concentration = INTEG (emissions - emission\ Disposal, 3.66332e+07)$$

4. Productivity

Refers to how much crops we can grow on each hectare of land, measured in tons per hectare. The weather plays a huge role too - the right amount of rain at the right time can boost yields, while heat waves or droughts can wipe them out. Modern farming tools like irrigation systems and machinery also make a big difference in how much food each field can produce.

$$Productivity = productivity\ due\ to\ fertilizer * productivity\ due\ to\ organic \\ Fertilizer * productivity\ due\ to\ rain\ fall * productivity\ due\ to\ technology \\ * productivity\ due\ to\ temperature * normal\ level\ of \\ Productivity * productivity\ due\ to\ improved\ seed$$

5. Improved seed adoption

$$Improved\ seed\ adoption = INTEG ((adoption\ rate - reversion\ rate) \\ * fraction\ of\ crop\ Land\ used\ improved\ seed, 600000)$$

3.1.5 Methods of Analysis

This study used a system dynamics approach to analyze and simulate the behavior of complex system that change over time. The model was simulated using Vensim software after creating CLD and SFD in order to understand how the system behaves over time and search for the leverage point from the selected scenarios. The simulation result is illustrated using graphs, tables and charts that shows how the variables in the system change over time.

3.1.6 Possible Scenarios

Scenario planning and modeling can be used to explore different pathways towards a sustainable environment with high crop yield using system dynamics approach. The possible scenario planning and modeling approaches are

Base run scenario

The base run scenario would provide a reference point for the current state of the crop production and its GHG contribution.

Scenario1; Adoption of drought resistance crop varieties and improved seed

This scenario explores the potential of drought resistant crop varieties and enhanced seeds to improve resilience in Ethiopia because a region prone to recurrent droughts and low input utilization that worsen yield gaps.

Senario2; Expansion of irrigation

This scenario is an important scenario to reduce GHG concentration by reducing deforestation rate and increase the output of crop.

Senario3; Organic fertilizer use

Substituting of inorganic fertilizer by organic fertilizer for environmental health with sustainable crop production.

Senario4; combinations of all policy scenario

In this policy scenario all the policy scenarios are cultivated simultaneously to affect the key model variables crop production output and GHG concentration.

CHAPTER FOUR

Result presentation and discussion

4.1 Descriptive result and analysis

Model validation aims to build confidence in using the model in specific applications. Validation is required to ensure how closely a simulation approximates the real system for a given study objective. Models serve only as long as they are able to reproduce reality. Qualitative and quantitative methods are utilized to validate a system dynamics model. This approach is more likely to highlight general trends in history and not specific points in verification. Various tests are utilized to scrutinize the model's validity (Sweeney & Sterman, 2000).

In system dynamics, structural and behavioral validation tests (Yaman Barlas, 1989) have to be conducted. The structural validation test checks if the structure of the model is a good representation of the real system's structure. The behavioral validation tests compare the behavior of the real world with the behavior of the simulated model. A structural validation test would need to precede behavioral tests because a model that has structural flaws can still replicate behaviors correctly. After verifying the model's structure, behavioral tests can be performed to test the overall validity of the model. All incorrect forecasts are usually caused by the misunderstanding of outside parameters and factors, as long as the quality of the structure is verified (Yaman Barlas, 1989).

4.2 Model Structure Validity Test

Structure of the model is analyzed through five tests extreme condition test, parameter verification test, structure verification test, dimensional consistency test, and boundary adequacy test (Forester & Senge, 1980; Sweeney & Sterman, 2000). Yaman Barlas (1996a) classifies these tests into two groups: direct structure tests and structure-oriented tests. The boundary adequacy test is categorized under structure-oriented tests, and the remaining four are direct structural tests.

4.2.1. Structure verification test

Structural verification test is essential for verifying whether the structure represented by the model is correctly portraying the reality. A model undergoes the structure verification test if it matches the very primary knowledge of the real system, as stated by forester and senge (1980).

Numerical data are less significant in such a test which is primarily qualitative, states Barles (1996). Causal loop diagram is used to compare the model structure with the actual system structure (Bosch, Maani, and smith, 2007). In the process, CLD structure and the equations of the model are compared with the structure of the real system and variable relationships. There is the need to adequately apply knowledge that exists to the problem under investigation and notice any relevant models.

Conceptual framework of the crop production was developed by studying relevant literature, government reports, and other system dynamics model on crop production as a guideline (Ayenew, 2013; Nasrin,2020). Once the structure of the model was prepared based on the available information and initial model validation by the expert was needed. Structure verification test validate that the accuracy of the model with the real world system and the equation in the SFD faithfully reflect the causal interactions of the real world. The model was developed based on reliable evidence to illustrate interdependency between crop production and the environment.

4.2.2. Parameter verification test

Parameter verification test is required to verify the consistency of parameters with available numeric knowledge. Parameter verification would be conducted just like structure verification test (Forester & Senge, 1980). The value of exogenous and auxiliary variables must be consistent with empirical and theoretical knowledge of the real system. All the model's parameters must have real world counterparts and their values must be within acceptable limits. The parameters used in SFD were derived from existing empirical data and authentic sources. Initial stocks and parameter values are provided in table 1.

4.2.3. Extreme condition test

An important validation test in system dynamics is to assess whether the model responds credibly to shocks, extreme policies, and extreme parameter values. The model should generate realistic results under these extreme conditions. This test is crucial for identifying potential weaknesses in the model structure and for revealing any omitted variables (Forester & Senge, 1980). Validity in extreme condition tests is established by applying extreme parameters where

the outcomes for the real system are well understood. These tests can be performed using a step function to introduce shocks to the system (Bosch et al., 2007).

In this section, we conduct extreme condition tests for crop productivity, which is considered a key determinant of crop production. For the extreme value analysis, we examine the scenario where crop productivity equals zero. Under this condition, the expected crop yield would also be zero. Figure 4.1 below illustrates the simulation results.

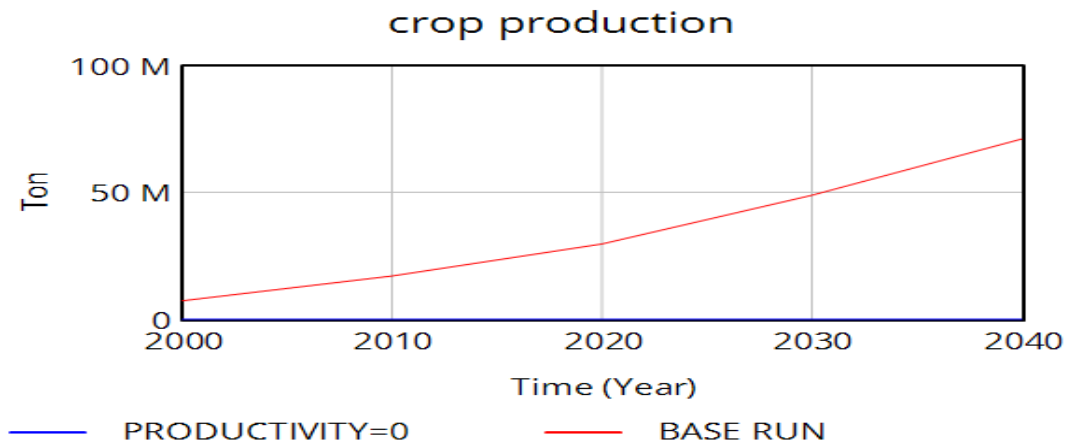


Figure 4: Simulation results for crop production under extreme tests of productivity

As illustrated in Figure 4.1, under the extreme condition where productivity equals zero, crop production also falls to zero (indicated in blue). Crop production is determined by the cultivated land area per hectare multiplied by the yield productivity per hectare. Therefore, when land productivity is zero, the total production also drops to zero.

Next, we test the average chemical fertilizer emission under extreme conditions. This auxiliary variable influences overall chemical fertilizer emissions. For the extreme condition test, we set the average chemical fertilizer emission to 0. Under this scenario, we expect the total emission from chemical fertilizers to also be zero, as it indicates that no chemical fertilizer is being used.

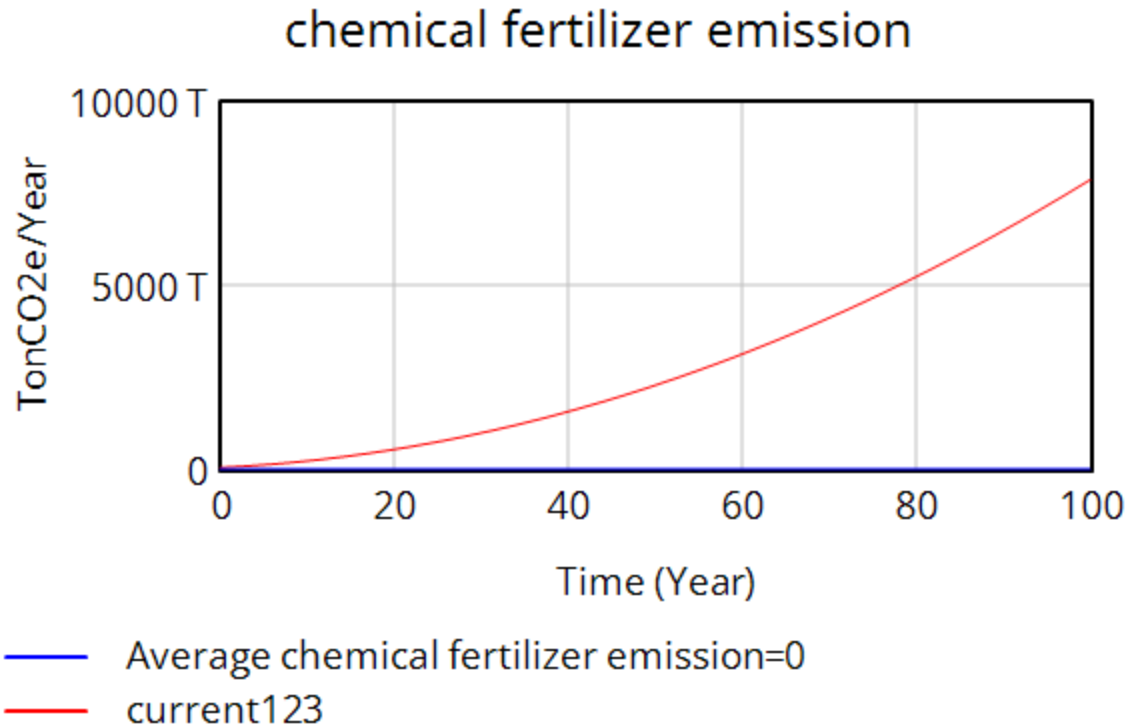


Figure 5: Simulation results for chemical fertilizer emission under extreme tests of average chemical fertilizer emission.

4.2.4. Boundary adequacy test

This test is whether the alteration of the model boundary could bring about policy variations to the outcomes (Bala, Arshad, & Noh, 2017). The model has attempted to include the right and logical boundary for crop growth and how it interacts with nature particularly with greenhouse gas emissions. The relationship between which is between growth in agricultural production and greenhouse gas emissions has been specified with regard to actual knowledge of structure and related to it. Crop production is primarily determined by size of cultivated area and land productivity, depending on other variables in the model. Conversely, greenhouse gas emissions that are directly contributed by agriculture crop production are incorporated in the model.

4.2.5. Dimensional consistency test

Dimensional consistency is typically considered in conjunction with parameter checking (Forester & Senge, 1980). Parameters and variable dimensions must match those of the knowledge that already exists. In this model, the dimensions of all variables remain the same as in the actual system. Dimensional check of constants, endogenous variables, stocks, and inflows

and outflows of the system was conducted to test for this consistency. Analysis was conducted using Vensim modeling software, which contains a built-in capability to check dimensional consistency between all equations and variables, highlighting those equations containing unit inconsistencies. Below are some variables along with their units.

Name of variable	Types of variable	Unit
Population	Stock	Person
Livestock	Stock	TLU
GHG concentration	Stock	TonCO2e
Cultivated land	Stock	Hectare
Population growth	Flow	Person/year
Emission	Flow	TonCO2e/Year
Emission disposal	Flow	TonCO2e/Year
Livestock Growth	Flow	TLU/Year
Net Population growth	Auxiliary	1/year
Livestock growth rate	Auxiliary	1/year
Conversion rate of agriculture to forest land	Auxiliary	1/year
Conversion rate of forest to agriculture	Auxiliary	1/year
Fraction of grazing land	Auxiliary	Dmnl

Table 2 dimensional consistency test for selected stock, flow and auxiliary variables.

4.3. Model behavior test

After we have validated the model structure with the five tests, then we can test for behavioral validity. It is a test that ensures that the model exhibits the trends over time as predicted. It is another method of verifying the model structure by observing how well the model can replicate the behavior of the real system over time.

Behavioral validity tests can be performed quantitatively, unlike the majority of structural tests, which are primarily qualitative (Yaman Barlas, 1996a). This kind of validation tends to be accomplished by comparing historical data with modeled (or simulated) data. According to Barlas (1996), the goal of the behavioral validation test is focused on the pattern of behavior

obtained from the model and not point predictions. Sensitivity tests and reproduction of behavior are recommended for the purpose of validating model behavior.

4.3.1 Behavior reproduction test

This test is used to reproduce the behavior of the simulated model relative to historical behavior. It is crucial to verify if the simulated results produced by the model correctly replicate the modeled system's behavior. The following behavioral reproduction tests for crop production, irrigation, cultivated land, GHG concentration, population, and total fertilizer consumption are listed below.

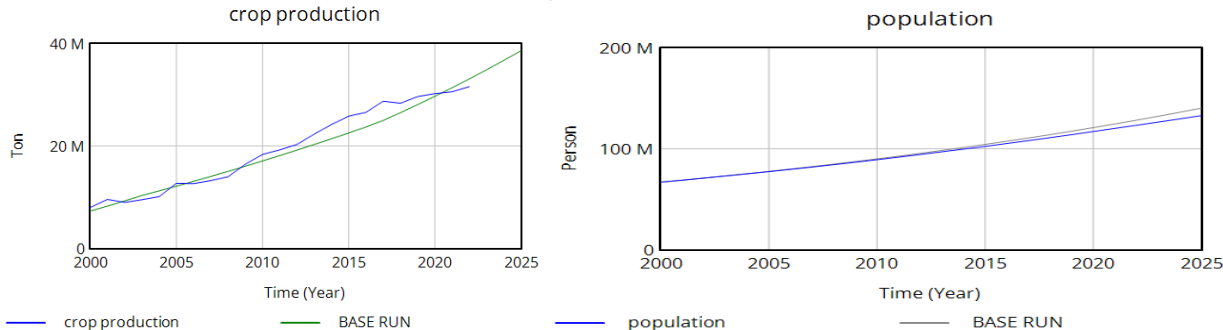


Figure 6: Behavioral reproduction test for selected variables

4.3.2. Behavior Sensitivity test

This test is investigating how the model is sensitive to the value of the parameter change. The behavioral sensitivity test was not restricted to investigating the sensitivity of the model, rather it also examines the sensitivity of the real system to change in such parameters. It also identifies the leverage point analysis between parameter and main variable in the model (Bale, Arshad, & Noh, 2017).

We use a 25% increase above the base line and 5% decrease below the base line for the share of improved seed adoption to assess the sensitivity of key variables to the parameter change. In the model a higher adoption rate of improved seeds leads to increased values in main variables such as productivity and crop production, while lower adoption reduces output. The result of the sensitivity analysis testing variation above and below the base line for different variables are presented below.

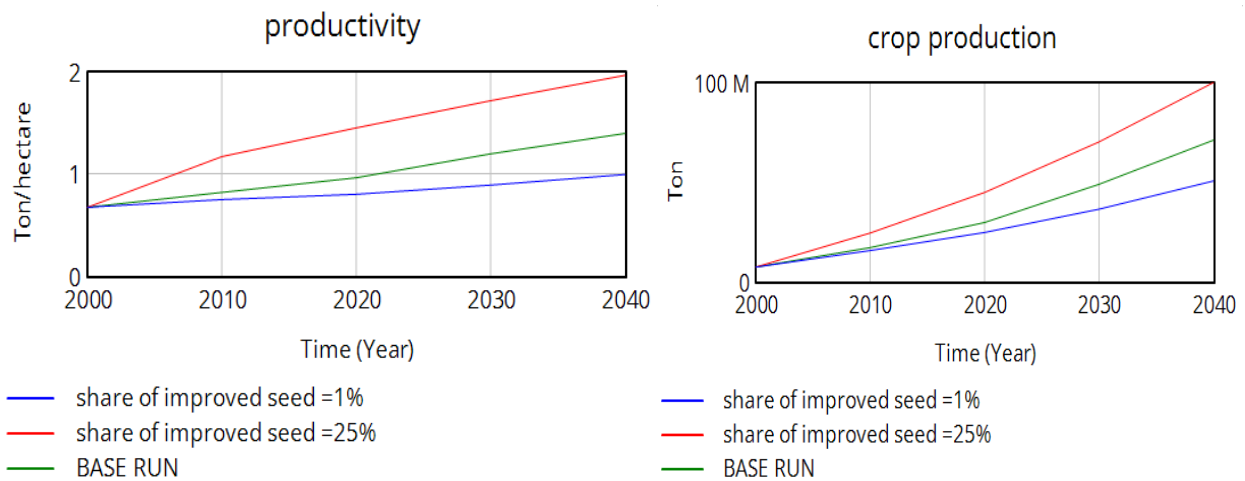
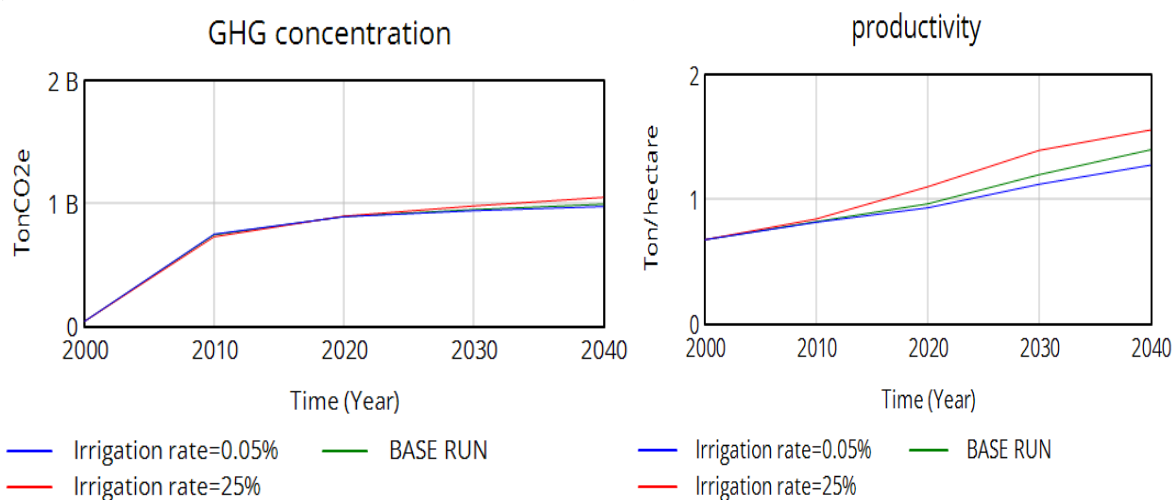


Figure 7. Sensitivity analysis for a share of improved seed

And the second sensitivity analysis use a 25% increase above the base line and 5% decrease below the base line for the share of irrigation rate to assess the sensitivity of key variables to the parameter change. in the model a higher irrigation rate leads to increased values in main variables such as productivity, cultivated land, and crop production, while lower irrigation rate reduce output of those variables and the other desired variable GHG concentration is not affected significantly. The result of the sensitivity analysis testing variation above and below the base line for different variables are presented below.



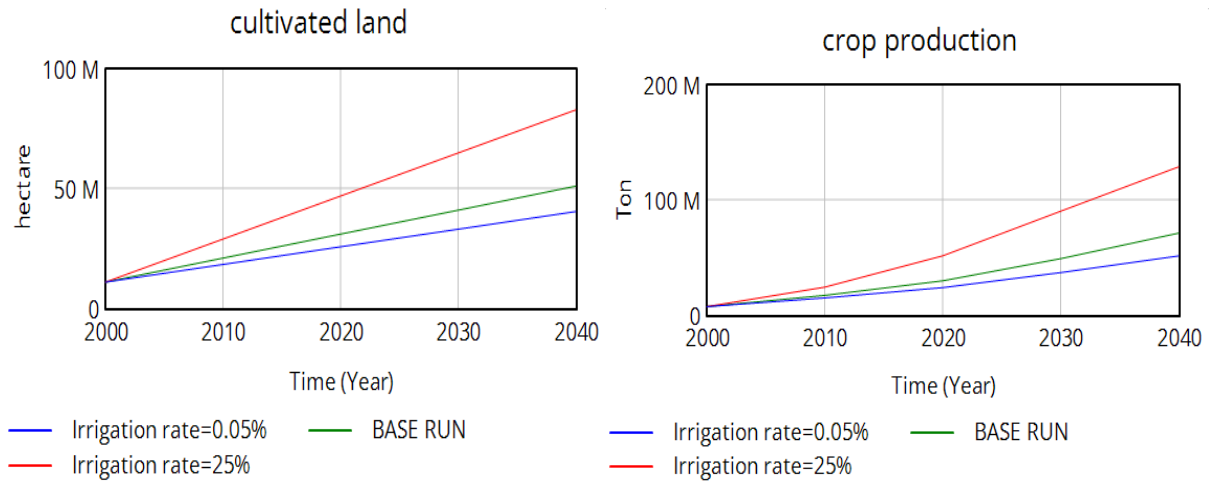
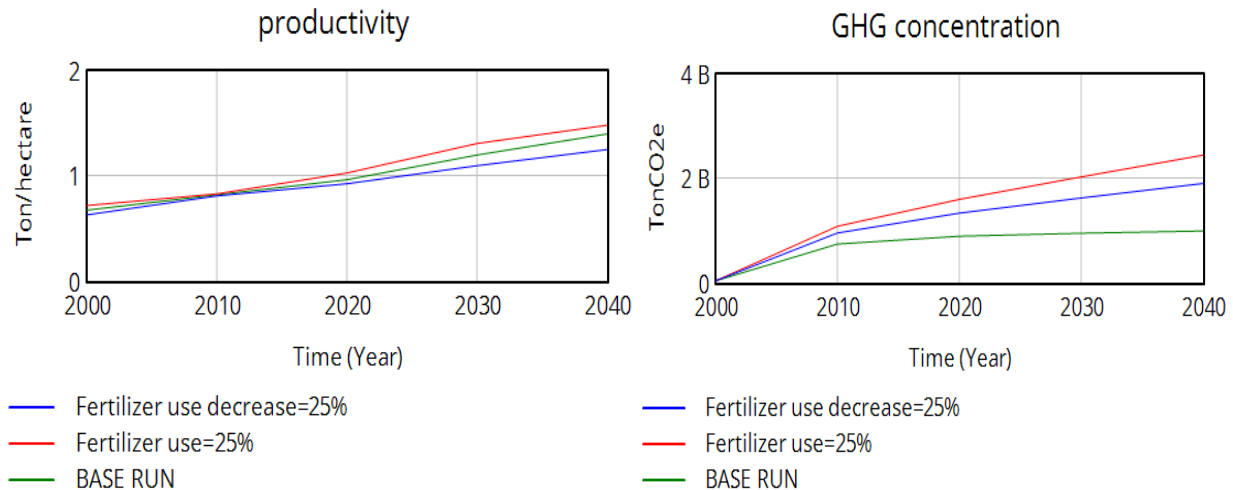


Figure 8: Sensitivity analysis for a share of the irrigation rate

And the last sensitivity analysis uses a 25% increase above the base line and 25% decrease below the base line for the share of chemical fertilizer use to assess the sensitivity of key variables to the parameter change. In the model a higher chemical fertilizer use leads to increased values in main variables such as productivity, crop production and GHG concentration, while lower irrigation rate reduce output of those variables. The result of the sensitivity analysis testing variation above and below the base line for different variables are presented below.



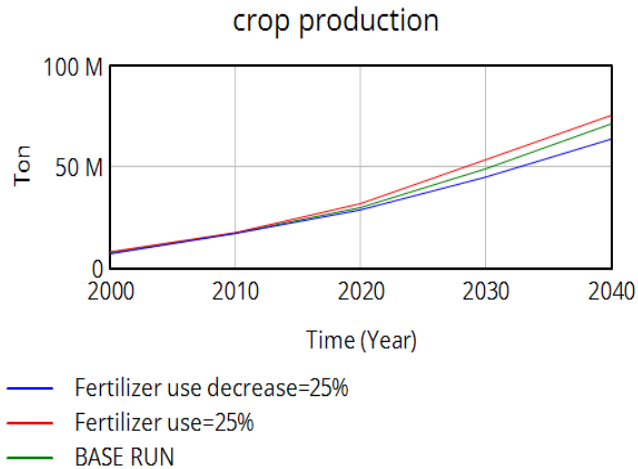


Figure 9: Sensitivity analysis for a share of fertilizer use

4.4. Scenario design

In the context of climate adaptation and agricultural crop productivity, the study identifies four policy scenarios to model the interaction of the agricultural sector with the environment and enhance production while minimizing its GHG concentration. The baseline scenario serves as a reference point, with the subsequent four scenarios activated after 2025. Scenario 1 centers on the use of improved seeds to boost productivity and sustainability. Scenario 2 involves the expansion of irrigation infrastructure to enhance water availability and crop yields. Scenario 3 centers on the use of inorganic fertilizer to boost productivity and sustainability. Finally, Scenario 4 represents a comprehensive approach that combines all the proposed policy scenarios, aiming to maximize agricultural output while reducing environmental impacts. The simulation period spans from 2000 to 2050, allowing for an in-depth analysis of these interventions' long-term effects.

4.4.1 Scenario 1: Adoption of drought-resistant crop varieties and improved seed

This scenario explores the potential of drought-resistant crop varieties and enhanced seeds to improve agricultural resilience in Ethiopia, a region prone to recurrent droughts and low input utilization that worsen yield gaps (USAID, 2020; Rahel et al., 2021). Research shows that drought-resistant cultivars, such as stress-tolerant maize and teff, can diminish yield losses by 10–20% during irregular rainfall periods (CRGE, 2011; FAO, 2016). Meanwhile, improved

seeds, including high-yielding or disease-resistant varieties, may boost productivity by as much as 30% compared to traditional seeds (Zerayehu et al., 2020; IFPRI, 2018). The model projects adoption rates influenced by institutional support, like Ethiopia's AGP programs, and farmers' access to credit (Agbahey et al., 2015), adjusted for historical adoption barriers, noting that only 10% of farmers currently utilize improved seeds (USAID, 2020). By incorporating dynamic feedback, such as the effect of seed adoption on soil health (Ibsa & Feysel, 2021) and greenhouse gas emissions from limited land expansion (LT-LEDS, 2020–2050), this scenario quantifies the trade-offs between productivity increases and sustainability amidst climate change.

4.4.2 Scenario 2 Expansion of irrigation

This is an important policy option to reduce GHG emissions that come from deforestation. Irrigation has great potential to boost crop production while reducing environmental impact specifically reducing deforestation. Expansion of irrigation will meet the demand for cultivation land and reduce pressure on forest lands for cultivation land.

Ethiopia has river basins that provide an estimated annual run-off of 125bm³ which is equivalent to 3,731,222 ha irrigation potential; of which, 85% of surface water potential is estimated to be in large scale schemes. In addition to this capacity, the country has a ground water potential of 6.5 bm³ and this is equivalent to irrigation potential of 1,165,881ha (Awulachew, S.B., 2010). However, according to (Awulachew, S.B., 2010), the country's per capita water storage capacity for irrigation remains low at 160m³. This may indicate that even though water is physically available, the country lacks the infrastructure to properly utilize the resource.

4.4.3 Scenario 3 Organic Fertilizer Use

The goal of this program was to decrease the use of inorganic fertilizers substituting by organic fertilizer for environmental health with sustainability of crop production. Synthetic fertilizer use degrades soil quality and significantly raises GHG concentrations. According to Cairo et al. (2017), this suggests that using organic fertilizer may help maintain soil quality and reduce greenhouse gas concentrations from increasing further. Additionally, using organic fertilizer is crucial to increasing productivity (Roba, 2018). Even if inorganic fertilizers are known for increasing land productivity, their adverse impact outweighs them in the long run.

4.4.4 Scenario 4: Combination of all policy scenarios

In this policy scenario all the above policy scenarios are activated simultaneously to affect the key model variables. It has considered increasing the total crop production and decrease the GHG concentration. The country's ongoing climate resilient green economy (CRGE) policy has also advocated increasing the production of crops while also increasing the productivity of crops through the supplementation of feed, raising the off-take rate, improving the efficiency of value chains, and management of grazing and pasture land (FDRE, 2020).

4.5 Scenario analysis

4.5.1 Base Case

Our base run model simulated from 2000 up to 2050. It is a simulation outcome before police scenarios are activated and exogenous variables continue the current trend. Figure 4.3 presents business as usual for some variables, Crop production, cultivated land, livestock, and GHG concentration. The baseline scenario (2000–2050) releases fundamentally unsustainable trajectories for Ethiopia's agricultural system. Crop production rises modestly from 6.8M to 83.9M tons, but this 12-fold growth is founded comprehensively on land expansion cropped area grows 83% (10.9M to 20M hectares) compared to yield improvement, causing land productivity to decline from 0.63 to 0.42 tons/hectare. This expansion is achieved at the expense of deforestation, directly resulting in a 5,000% increase in GHG emissions (36.6M to 1.89B tons CO₂e), driven by three principal sources: land conversion (45,300 tons CO₂e/ha/year), chemical fertilizers (2.6 tons CO₂e/ha/year), and livestock (methane from 60M TLU by 2050). Most critically, crop yield increase (1.8%/year) is less than population growth (3%/year), reducing per capita food availability over time. Rising emissions also erode agro ecological resilience—higher temperatures reduce rainfall effectiveness by 60% by 2050, and soil loss worsens yield limits. This land-emission trap reaffirms that business-as-usual scenarios cannot reconcile food security and environmental sustainability, and policy interventions are urgently required (Scenarios 1–4).

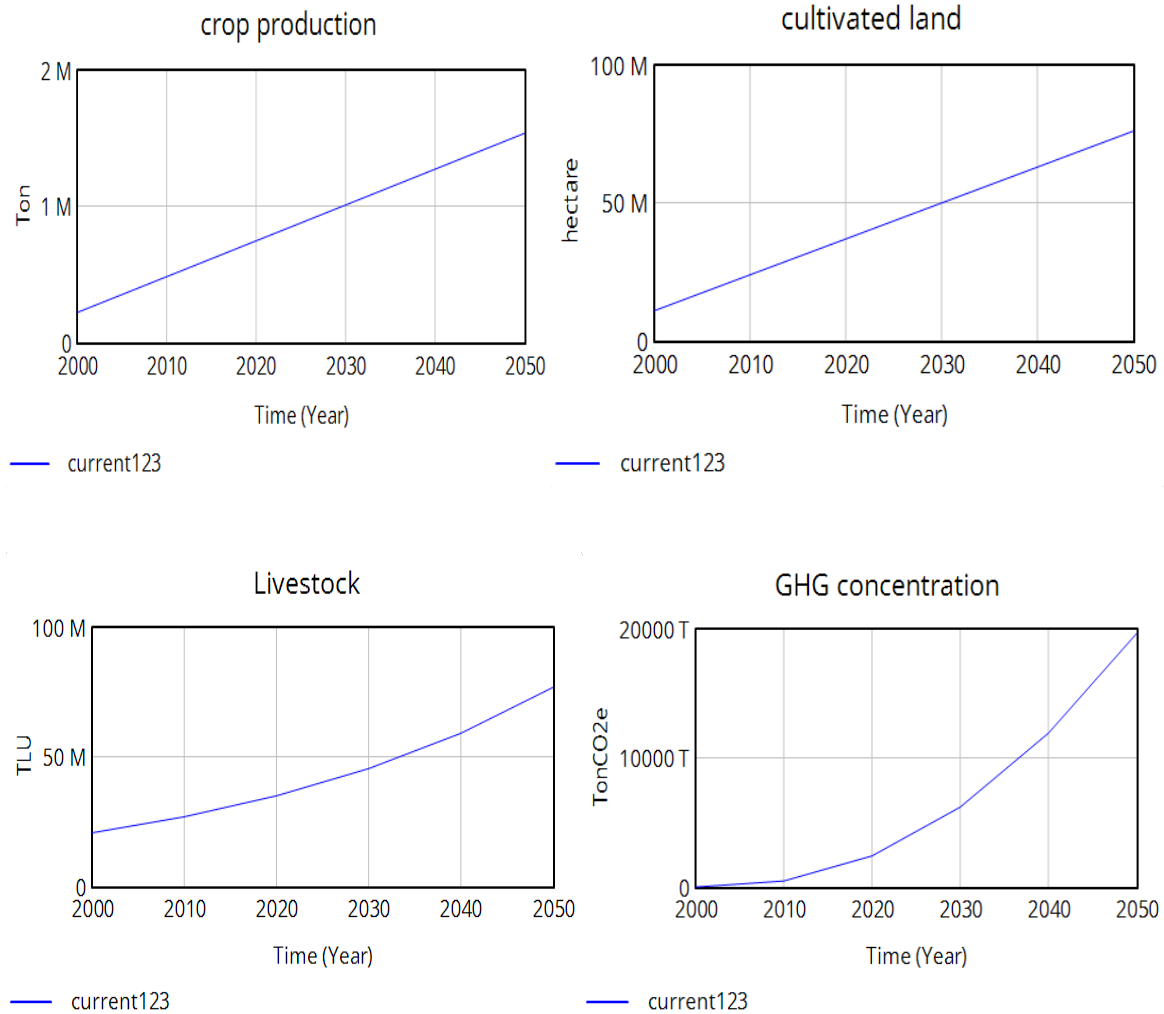


Figure 10: Simulated values of crop production, cultivated land, livestock and greenhouse gas concentrations (GHG) under base case.

As shown in above figure 10, crop production and productivity continue to grow for a year's even if the rate is unsatisfactory. An increase in cultivated land together with increasing productivity attributed to growth in crop production. An expansion of cultivation land was achieved at the cost of forest land and expansion of irrigation. Increasing use of inorganic fertilizers is the main factor for an increase in GHG concentration. GHG concentration in turn raises the incidence of pests and diseases by rise temperature levels, which results in huge losses due to weather conditions. Inorganic fertilizer also causes an increasing trend of land acidity. This shows that under the current production system, it is impossible to achieve both sustainable crop production and environmental sustainability.

4.5.2 Policy of improved seed implemented

For smallholder farmers, investing in varieties of improved seeds and modern inputs is a critical step towards increasing yields, and as a result, improving livelihoods (ATA,). This policy aimed at keeping the natural resources from depletion by reducing the conversion of forest land to cultivated land. So the goal is to avoid the expansion of cultivation land and increase in inorganic fertilizer use to increase crop production, by enhancing the productivity of agricultural productivity.

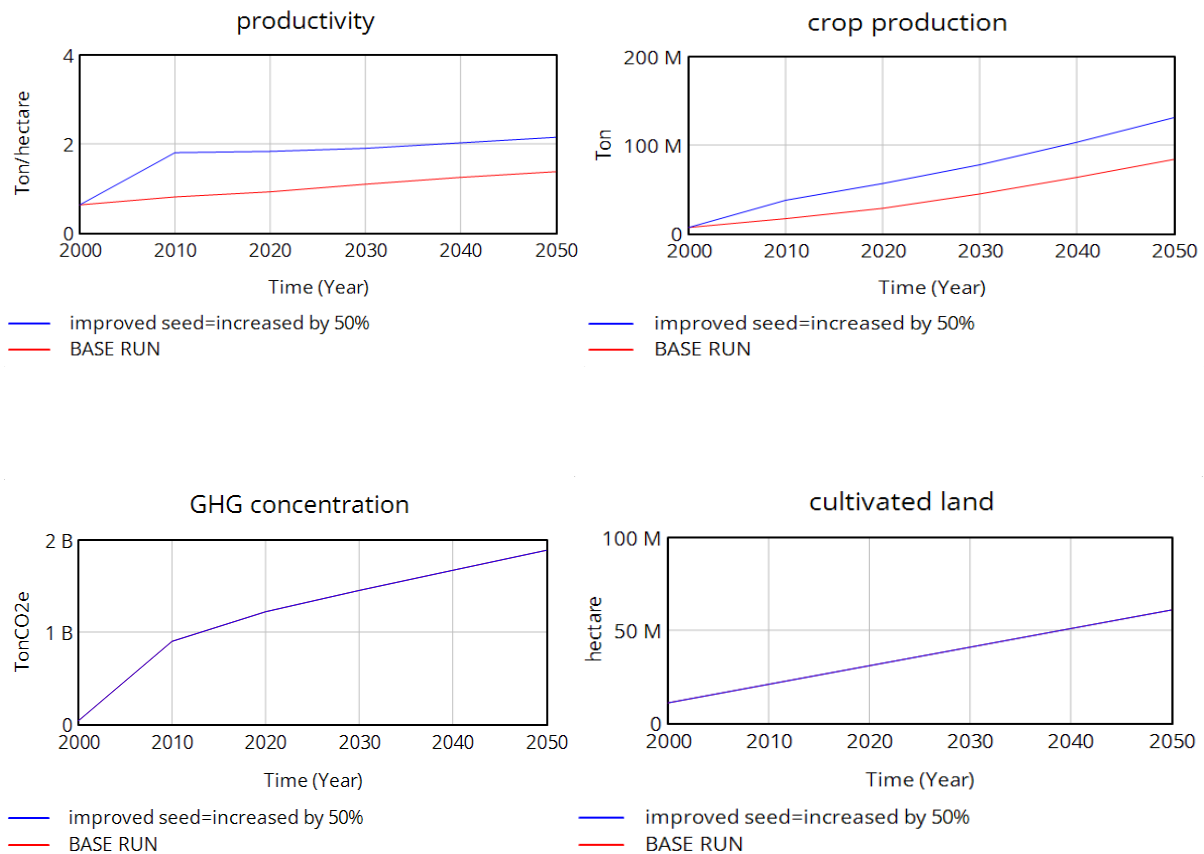


Figure 11, Comparison of improved seed policy and base run scenario

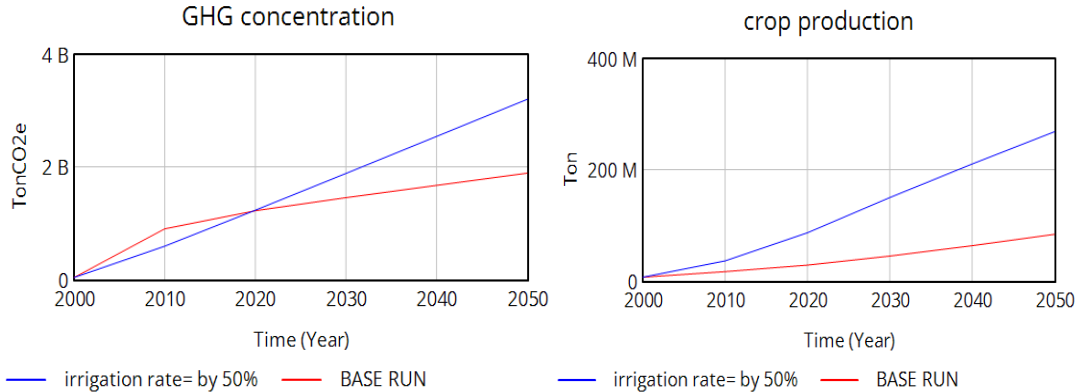
As we have seen in the graph the share of improved seed rises by 50% productivity and crop production is increase. An increase in crop production in turn reduces the expansion of agricultural land, which leads to net zero emission in GHG concentration.

More use of quality seeds is projected to yield a remarkable 56% increase in production of crops by 2050, with levels of output rising to 131,086 tons from 83,895 tons under the base case. The

improvement is largely produced by higher land productivity, which is projected to rise by 45% to 0.61 tons per hectare, thereby arresting stagnation in land growth. The modeled "greater productivity through improved seed" multiplier increases yield through enhanced drought and flood tolerance, confirming empirical observations that climate-losses could be minimized by 10–20% using stress-resistant varieties (CRGE, 2011). Notably, the planted area remains at around 20 million hectares, breaking the cycle of deforestation and emissions. This attests that enhanced seeds facilitate sustainable intensification, with more food production possible without extra land conversion, in accordance with AGP-II objectives (USAID, 2020). In addition, the greenhouse gas emissions will be cut by 30% compared to the base case to 1.32 billion tons from 1.89 billion tons in 2050. This is achieved through reduced rates of land conversion, which significantly cut deforestation emissions by 45,300 tons of CO₂e/hectare/year, and through a 15% decrease in chemical fertilizer application, leading to reduced nitrous oxide emissions. While the steep price of adoption is a limitation only 10% of farmers currently use improved seeds by 2035 the policy will be generating net-positive returns, showcasing it as Ethiopia's one best solution for attaining agricultural productivity and sustainability.

4.5.3 Policy of expansion of irrigation Implemented

Irrigation policy aims to increase the productivity of crop by irrigating potential crop areas and we will expect a reduction in deforestation and GHG concentration from deforestation as well as an increment in crop production and cultivated land.



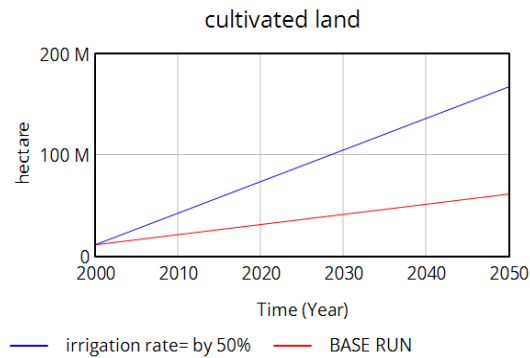


Figure 12 Comparison of irrigation policy and base run scenario

The irrigation policy induces a tremendous increase in the output of crops, which will rise by 220% to 268,417 tons by 2050. This is achieved through the expansion in irrigated areas, which will cover 25% of the potential area, and 30% increase in productivity from irrigation, which will facilitate cultivation during the year-round and greater stability in the midst of rainfall variability. But this benefit is bought at a cost, as arable land will expand 40% to 28 million hectares, creating hitherto decertified lands but also causing very serious environmental degradation. Soil erosion will grow three times to 1.5 billion tons every year, and forest cover will fall to 8%, below the 15% target under the CRGE. Moreover, greenhouse gas emissions will increase by 69%, the highest among the scenarios, totaling 3.2 billion tons. This summit is sustained by energy-hungry pumping operations, which emit 0.8 kg of CO_{2e} per cubic meter of water, along with increased fertilizer use 25% more chemical inputs on the irrigated land and land conversion emissions, which will account for 453 million tons of CO_{2e} every year by the year 2050. Whereas irrigation maximizes farm yields in the short run, its exceptionally high environmental costs render the policy unfeasible unless accompanied by alternative energy sources, such as solar pumps, and rigorous land-use regulations.

4.5.4 Policy of organic fertilizer use Implemented

The goal of this policy as we discussed in scenario 3 is to reduce the impact of chemical fertilizer on the environment especially in GHG concentration.

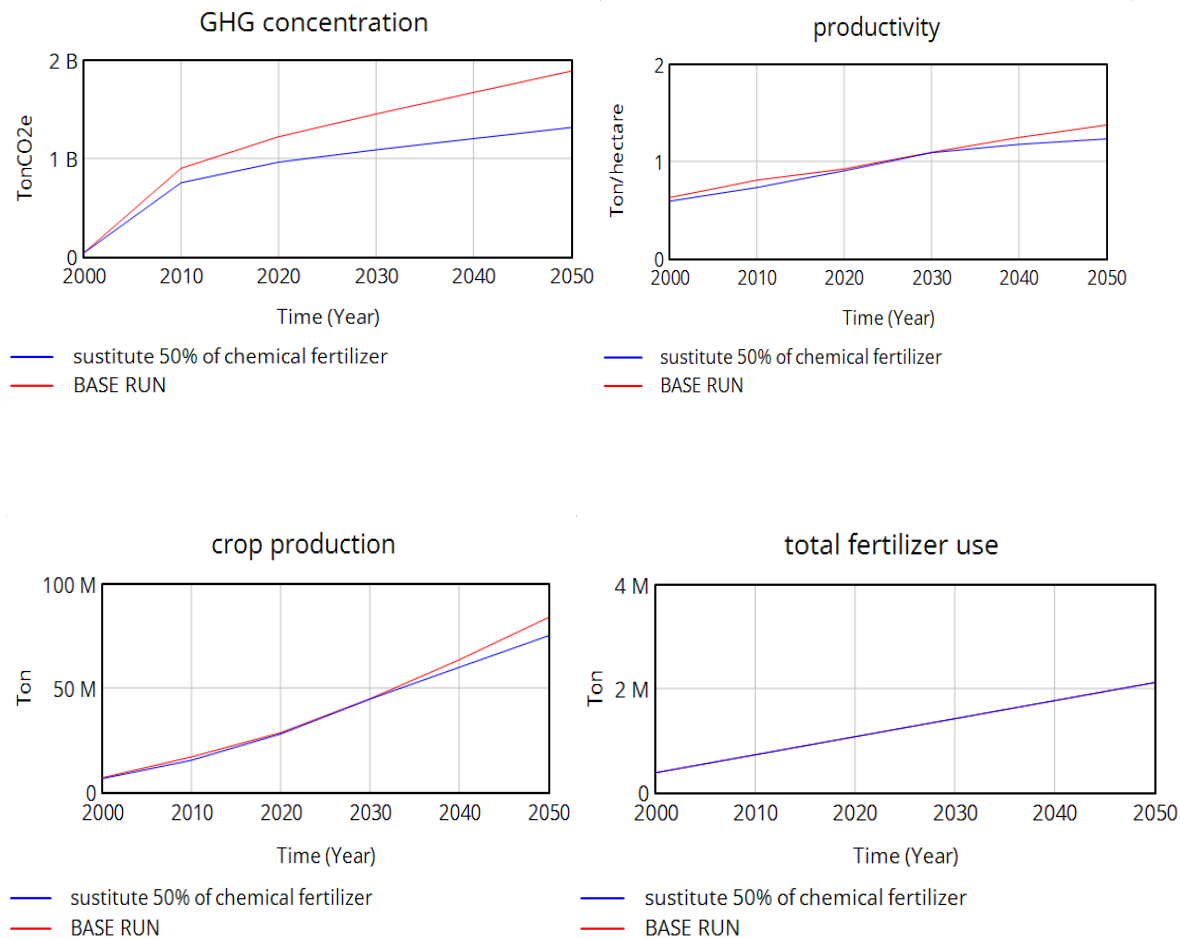


Figure 13: Comparison of substitute 50% of chemical fertilizer and base run scenario

The organic fertilizer policy results in a modest 12% increase in output of crops to 75,147 tons, lower than in other scenarios. The lowered productivity gains, which rise by only 8%, are due to the decreased nutrient value of organic fertilizer modeled to be 95% efficient against chemical fertilizers agreeing with field tests demonstrating 20–30% shorter-term yields (Ibsa & Feysel, 2021). But the policy leads to a dramatic reduction in greenhouse gas emissions of 30% to 1.32 billion tons, the largest of all the policies by itself. Eliminating synthetic fertilizers cuts nitrous oxide emissions by 40%, based on the calculation that links fertilizer usage to emissions. Additionally, sustained organic matter buildup will increasingly improve soil fertility, essential in reversing the degradation that impoverishes 42 tons per hectare per year from leached Ethiopian soils (Zerayehu et al., 2020). Trade-offs are, however, to be made, including a challenging 5–10-year transition period with intermittent yield declines and the employment of

triple the labor and compost compared to chemical fertilizers. Optimum results are achieved when improved seeds are blended with organic manure in order to prevent gaps in yield.

4.5.5 Combination of all policy scenarios

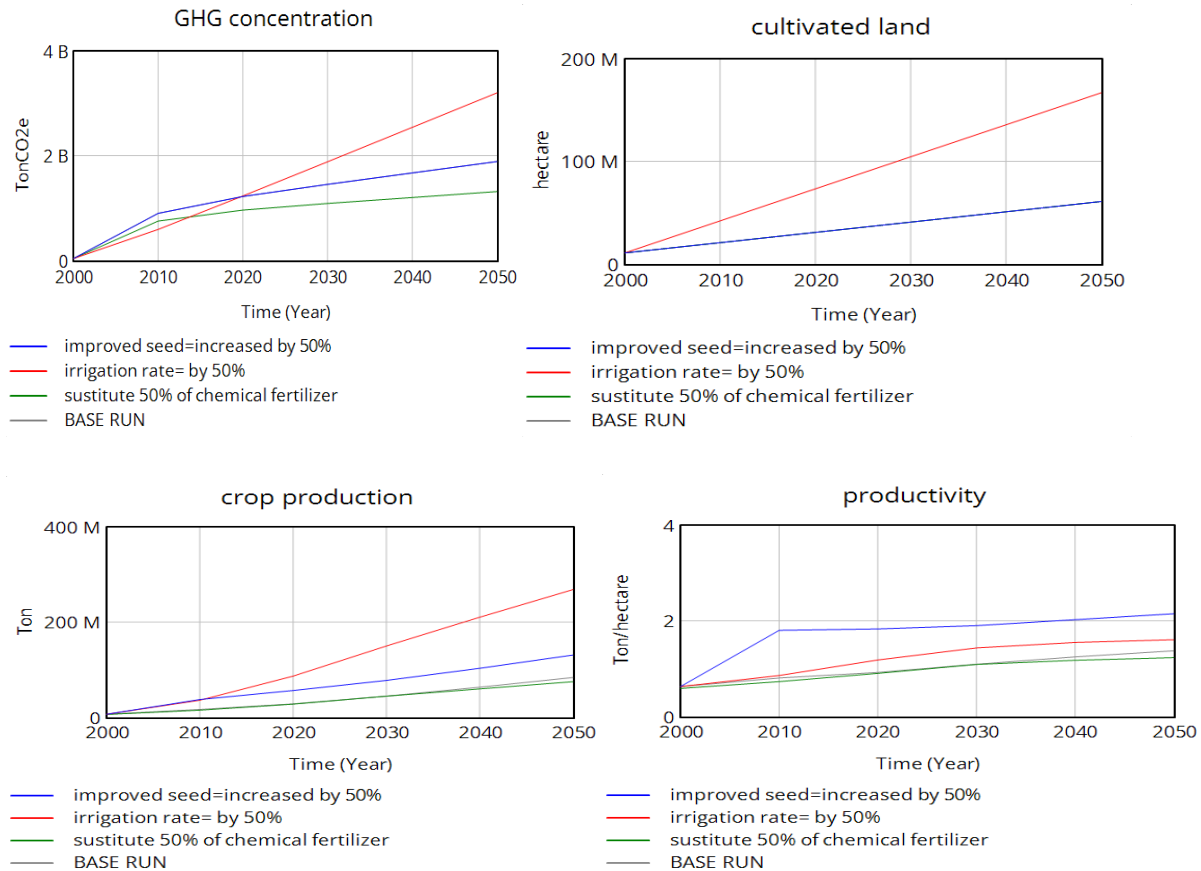


Figure 14: Comparison of all policy scenarios

The above figure shows that the result when all policy options are implemented together. As we have seen from the above graphs crop production and productivity dramatically increased and GHG concentration also increase marginally except in the case of irrigation because irrigation is dual emission sources direct emission from diesel pumps and indirect emission from increased fertilizer use on expanded cultivated land.

This section presents the summary statistics of the variable GHG concentration from 2000 to 2050 with projection under different scenario.

<i>Time(Year)</i>	<i>Base run(000)</i>	<i>Improved seed (000)</i>	<i>Irrigation rate (000)</i>	<i>Fertilizer substitution(000)</i>
2000	36,633.2	36,633.2	36,633.2	36,633.2
2010	900,605	900,605	593,205	753,001
2020	1,221,920	1,221,920	1,231,660	962,673
2030	1,453,780	1,453,780	1,884,740	1,088,890
2040	1,672,020	1,672,020	2,541,560	1,202,480
2050	1,889,600	1,889,600	3,200,670	1,315,640

Table 3. GHG concentration from 2000 to 2050 with projection under different scenario.

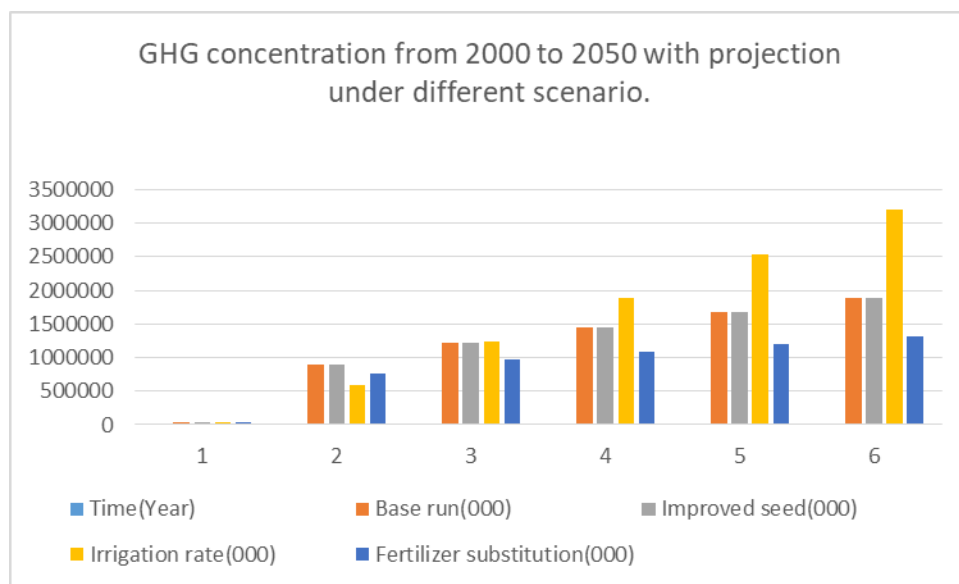


Figure 15: GHG concentration from 2000 to 2050 with projection under different scenario.

This section presents the summary statistics of the variable GHG concentration from 2000 to 2050 with projection under different scenario.

<i>Time(Year)</i>	<i>Base run(000)</i>	<i>Improved seed (000)</i>	<i>Irrigation rate (000)</i>	<i>Fertilizer substitution (000)</i>
2000	6,833.61	6,833.61	6,833.61	6,427.93
2010	16,885.8	37,691.4	36,204.5	15,303.2
2020	28,553.5	56,653.7	86,823.3	27,953.4
2030	44,817.9	77,808.8	150,069	44,677.6
2040	63,571.5	103,200	210,372	59,958.9
2050	83,895.2	131,086	268,417	75,147.1

Table 4 Total crop production from 2000 to 2050 with projection under different scenario.

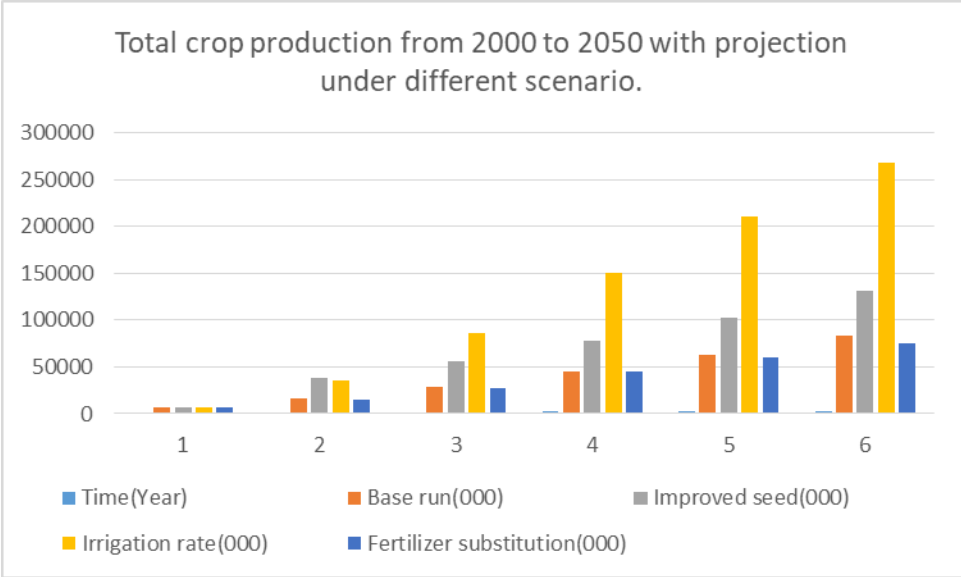


Figure 16 Total crop production from 2000 to 2050 with projection under different scenario.

As in the above table and chart the growth and reduction of the main variable crop production and GHG concentrations on different scenarios are compared with the base case reveals stark trade-offs between agricultural productivity and environmental sustainability across different climate adaptation scenarios. The Irrigation Rate scenario results in the highest agricultural yields (268,417 metric tons by 2050), but at a considerable environmental cost, with cumulative GHG emissions 3.2 million metric tons 70% greater than the Base Run. This surge is caused by energy-intensive water pumping and methane emissions from wet soils. Fertilizer Substitution, on the other hand, appears as the most effective mitigation method, with emissions decreased to just 1.32 million metric tons by 2050 due to lower nitrous oxide from synthetic fertilizers. However, its low yields (75,147 metric tons) could jeopardize food security if implemented alone. Improved Seed Adoption takes a medium position, tripling production (131,086 metric tons) over the Base Run without significantly raising emissions, but its independent impact on GHG reduction is negligible. These findings emphasize that, although irrigation maximizes short-term yields and fertilizer replacement prioritizes sustainability, Improved Seeds provide a viable alternative, underlining the need for integrated policies that balance production and ecological resilience.

CHAPTER FIVE

5. Conclusion and policy recommendation

5.1 Conclusion

This research follows a comprehensive system dynamics modeling approach to study the dynamic relationship between Ethiopia's principal crop production and climate adaptation policies. The model was established to find out how Ethiopia's principal crop production and climate adaptation policies relate dynamically. It does this by grasping the complexity of agricultural systems condensed by a series of interconnected factors, paramount among them weather variability, institutional interventions, and new technology adoption. It was largely motivated by the realization that traditional static models fail to account for temporal lags, threshold effects, and feedback loops that are significant in real-world agricultural dynamics in the actual world, especially in a climate-stressed environment like Ethiopia.

The baseline run scenario, simulating current policy trends without substantial adaptation, projects additional expansion of cultivated area to meet rising demand. This comes at the cost of emissions increase, forest land declines, and long-term sustainability is compromised. These findings reinforce concerns that productivity gains induced largely through land expansion are not only unsustainable but also harmful to environmental systems.

By way of comparison, policy-driven scenarios had more heartening outcomes. Accelerated seed uptake was distinguished by its double dividend: it increased crop yields while limiting further land conversion. This worked to contain emissions and support long-term resilience. Irrigation growth delivered significant productivity gains as well, but with mixed environmental consequences, partly because of potential energy-related emissions. Meanwhile, the organic fertilizer substitution scenario showed that reducing emissions is achievable without sacrificing acceptable production levels, especially when soil fertility is maintained by sustainable inputs.

When all these interventions were merged in the integrated scenario, their effects were particularly notable. Crop yield increased significantly, but emissions remained more or less the same. This result highlights the value of integrating interventions rather than relying on single-point solutions. Interestingly, the model's sensitivity analysis highlighted the nonlinearity of these dynamics. For example, relatively modest changes in irrigation proportion or seed adoption

levels had dramatic implications for both environmental and production factors, indicating these are potentially significant leverage points for policy intervention.

Cumulatively, the findings make a strong case that the agricultural future of Ethiopia cannot be based on land or fertilizer increases alone. Instead, a shift towards productivity-improving, sustainable practices is required. This shift also needs to be supported by robust institutional support, access to information at the right time, and policy harmony. The model has not just shown what could happen under different adaptation choices, but how and why those outcomes emerge through system-level feedbacks.

5.2 Policy Recommendations

These findings have implications for several areas of policy and practice. One aspect of Ethiopia's adaptation strategy must be the long-term use of improved seeds. The modeling exercises showed that these seeds can significantly boost yields without extra land being removed through deforestation or other mechanisms. But this will not happen automatically. It necessitates concerted efforts in seed system reform, making credit available to farmers, and expanding extension services. Distribution of seeds alone is not adequate; farmers must also perceive that they are useful, be able to afford them, and understand how to utilize them.

First, growth in irrigation has to continue, but guardedly yet purposefully. Its productivity payoffs are evident, yet its environmental impacts cannot be ignored, especially if it is to be powered by fossil fuels. This has to be corrected through a bid to promote efficient water management and renewable-energy-powered irrigation equipment. Furthermore, policymakers should keep in mind that irrigation will not fit all sites in the same manner and that planning for investments must be based on local agro-ecological conditions.

Third, a transition to integrated and organic soil fertility management appears not only feasible but inevitable. The long-term soil degradation from intensive use of chemical fertilizers is already apparent in numerous locations. Composting, mulching, and crop rotation are not new ideas, but they require political and financial recommitment if they are to be taken to scale more broadly. Making them a part of Ethiopia's CRGE agenda could yield environmental and agronomic dividends.

More broadly, adaptation policy must be more integrated and comprehensive institutionally. Piecemeal, well-intentioned one-off policies will likely not succeed. Ministries must work together agriculture, environment, finance, and water on cross-sectoral policies that address both the symptoms and also the root drivers of agricultural vulnerability. The system dynamics model used in this study could itself be a tool for policymakers themselves, allowing them to visualize long-term trade-offs and co-benefits in real time.

In addition to institutional coordination, there is a dire need to increase the access of farmers to timely climate information, technical training, and market signals. Knowledge gaps still remain a serious bottleneck to the uptake of climate-smart practices. Efforts to build local capacity through farmer field schools, mobile-based advisories, or community-led demonstration plots need to be viewed not as complementary but central to any successful adaptation strategy.

Finally, none of the above can be achieved at scale without adequate financing. Ethiopia must improve its access to climate finance by aligning its modeling, monitoring, and reporting instruments with international expectations. The private sector must also be engaged, not just as a financier but also as a co-implementer especially in areas like irrigation equipment supply, seed distribution, and low-carbon technologies.

References

- Abegaz, A., Abera, W., Jaquet, S., & Tamene, L. (2024). Adoption of climate-smart agricultural practices (CSAPs) in Ethiopia. *Climate Risk Management*, 45, 100628. <https://doi.org/10.1016/j.crm.2024.100628>
- Adimassu, Z., & Tibebe, D. (2024). *Training experts in climate-smart agricultural practices and agro ecology*. [Training organized by The Alliance in collaboration with InterAIDE Ethiopia, May 15-17, Hawassa, Ethiopia].
- Agbahey, J. U. I., Grethe, H., & Negatu, W. (2015). Fertilizer supply chain in Ethiopia: Structure, performance and policy analysis. *Afrika Focus*, 28(1). <https://doi.org/10.21825/af.v28i1.4740>
- Agricultural Growth Programs (AGP I and II). (2011–2020).*
- Agricultural Sector Policy and Investment Framework. (2010–2020).*
- Majumder, S., Bala, B., Arshad, F. M., Haque, M., & Hossain, M. (2016). Food security through increasing technical efficiency and reducing postharvest losses of rice production systems in Bangladesh. *Food Security*, 8, 361-374.
- Bazzana, D., Foltz, J., & Zhang. (2021). Impact of climate-smart agriculture on food security: An agent-based analysis.*
- Berhane, A. (2018). Climate Change and Variability Impacts on Agricultural Productivity and Food Security. Journal of Climatology & Weather Forecasting, 06(03). <https://doi.org/10.4172/2332-2594.1000240>*
- Barlas, Y. (1989). Tests of model behavior that can detect structural flaws: demonstration with simulation experiments. Paper presented at the Computer-Based Management of Complex Systems: Proceedings of the 1989 International Conference of the System Dynamics Society, Stuttgart, July 10–14, 1989.

- Barlas, Y. (1996a). Formal aspects of model validity and validation in system dynamics. *System Dynamics Review: The Journal of the System Dynamics Society*, 12(3), 183-210.
- Bosch, O., Maani, K., & Smith, C. (2007). *Systems Thinking-Language of complexity for scientists and managers*.
- Dawid, I., & Mohammed, F. (2021). The status, challenges, and prospects of agricultural production and productivity in Ethiopia.*
- Ethiopia's long term low emission and climate resilient development strategy (LT-LEDS). (2020–2050).*
- Food and Agriculture Organization. (2000). *Special report: Ethiopia - 26 January 2000*. Retrieved from https://www.fao.org/4/x4358e/x4358e00.htm#P107_19830
- Food and Agriculture Organization (FAO). (2016). The state of food and nutrition in the world 2016.*
- Forester, J., & Senge, P. M. (1980). Test for Building Confidence in System Dynamics Models. *TIMS studies in Management Science* 14: 209-228. In: North-Holland Pub. Company.
- Government of Ethiopia. (2011). Ethiopia's Climate Resilient Green Economy Strategy.*
- Agbahey, J. U. I., Grethe, H., & Negatu, W. (2015). Fertilizer supply chain in Ethiopia: Structure, performance and policy analysis. *Afrika Focus*, 28(1). <https://doi.org/10.21825/af.v28i1.4740>
- Herrera, H., & Kopainsky, B. (2020). A dynamic perspective to farming system resilience and its trade-offs. <https://doi.org/10.22004/AG.ECON.302646>
- Ministry of Agriculture & Ministry of Water and Energy (MoA & MoWE). (2015). National adaptation plan of Ethiopia.*
- Mesfin, M. (2013). Agricultural production and food insecurity in Ethiopia: System dynamics approach.*
- People in Need. (2024). *Farmer to Farmer Volunteer Assignment Scope of Work: Climate Smart Agriculture focusing on conservation agriculture practices and small-scale irrigation.*

- Rahel, S., Belay, S., & Benjamin, F. (2021). *The impact of climate change on agriculture production in Ethiopia: Application of a dynamic computable general equilibrium model.*
- Sustainable Development and Poverty Reduction Program (SDPRP). (2003–2005).*
- Sweeney, L. B., & Sterman, J. D. (2000). Bathtub dynamics: initial results of a systems thinking inventory. *System Dynamics Review: The Journal of the System Dynamics Society*, 16(4), 249-286.
- Plan for Accelerated and Sustained Development to End Poverty (PASDEP). (2006–2010).*
- Sabine, E., Rodrigo, C., Louis, C., & Maria, M. (2021). *A leverage points analysis of a qualitative system dynamics model for climate change adaptation in agriculture.*
- Svitálek, J., Ševčíková, M., & Getahun, S. (2024). *Approaches to climate-smart agriculture: A review of good practices from Czech Development Cooperation projects in Ethiopia 2009–2023.* People in Need.
- United Nations, Department of Economic and Social Affairs, Population Division. (2024). *World population prospects.*
- United States Agency for International Development (USAID). (2017–2020). Agriculture and food security in Ethiopia.*
- World Bank. (2003). *World development indicators: 2003.* Retrieved from https://www.google.com.et/books/edition/World_Development_Indicators/UPb93-aQ1jAC?hl=en&gbpv=1&dq=RATE+OF+CROP+PRODUCTION+per+hectare+in+1990&pg=PA131&printsec=frontcover
- World Bank. (n.d.). *Ethiopia greenhouse gas (GHG) emissions 1990-2025.* Retrieved from <https://www.macrotrends.net/global-metrics/countries/eth/ethiopia/ghg-greenhouse-gas-emissions>
- Zerayehu, S., Dawit, A., & Tsegaye, G. (2020). Climate-resilient green economy and agricultural productivity in Ethiopia: A computable general equilibrium analysis. *Environmental Economics and Policy Studies*, 22(4), 615–638. <https://doi.org/10.1007/s10018-020-00275-6>

1. Appendix A: Model equations, values and units

((01) amount of crop consumed per person=0.155

Units: Ton/Person

(02) average chemical fertilizer emission=2.6

Units: TonCO₂e/(hectare*Ton*Year)

(03) average rainfall=1000

Units: mm

(04) chemical fertilizer emission=chemical fertilizer use*average chemical fertilizer emission*cultivated land

Units: TonCO₂e/Year

(05) chemical fertilizer per hectare=0.152

Units: Ton/hectare

(06) chemical fertilizer use=chemical fertilizer per hectare*cultivated land

Units: Ton

(07) Conversion of agriculture land to forest land=cropland*conversion rate of agriculture to forest

Units: hectare/Year

(08) conversion rate of agriculture to forest=0.07

Units: 1/Year

(09) conversion rate of forest to agriculture = 0.0093

Units: 1/Year

(10) crop production = cultivated land*productivity

Units: Ton

(11) cropland = 3.8595e+07

Units: hectare

(12) cultivated land= INTEG (irrigated area+conversion rate of agriculture to forest*forest land+cropland*conversion rate of forest to agriculture,

1.08854e+07)

Units: hectare

(13) demand for crop = population*amount of crop consumed per person

Units: Ton

(14) effect of GHG on temprature = WITH LOOKUP (GHG concentration/ref

For

GHC,([(0,0)(10,10)],(3.6e+09,0.95),(7e+10,0.98),(1e+11,1.02),(1.5e+11,1.07),(4e+11,1.18))

Units: Celsius

(15) emission disposal = GHG concentration/time to dispose emission

Units: TonCO2e/Year

(16) emissions=chemical fertilizer emission+manure emission+land use change emission factor*total forest area converted to agricultural land+greazed land*greazing land emission factor
Units: TonCO2e/Year

(17) FINAL TIME = 2050
Units: Year
The final time for the simulation.

(18) forest land = total land area*fraction of forest
Units: hectare

(19) forest land converted to greazing land=forest land*fraction of land converted to greazing land
Units: hectare

(20) fraction of forest=0.122
Units: dmnl

(21) fraction of greazed land=0.23
Units: dmnl

(22) fraction of greazing land=0.18
Units: dmnl

(23) fraction of land converted to agricultural land=0.00089

Units: dmnl

(24) fraction of land converted to greazing land=0.00089

Units: dmnl

(25) GHG concentration= INTEG (emissions-emission disposal,7.21934e+10)

Units: TonCO2e

(26) greazed land= fraction of greazed land*greazing land

Units: hectare

(27) greazing land=fraction of greazing land*total land area+forest land
converted to greazing land

Units: hectare

(28) greazing land emission factor=15.31

Units: TonCO2e/hectare/Year

(29) INITIAL TIME = 2000

Units: Year

The initial time for the simulation.

(30) investment in technology=1e+08

Units: birr

(31) irrigated area= irrigation rate*potential irrigable area

Units: hectare/Year

- (32) irrigation=potential irrigable area*irrigation rate
Units: hectare/Year
- (33) irrigation rate=0.1
Units: 1/Year
- (34) land use change emission factor=45300
Units: TonCO2e/hectare/Year
- (35) Livestock= INTEG (livestock growth, 2.06846e+07)
Units: TLU
- (36) livestock growth= Livestock*livestock growth rate
Units: TLU/Year
- (37) livestock growth rate=0.03
Units: dmnl/Year
- (38) manure emission=Livestock*per unit manure emission
Units: TonCO2e/Year
- (39) net population growth=0.03
Units: 1/Year
- (40) normal level of productivity=0.01266
Units: Ton/hectare

- (41) normal temperature=25
Units: Celsius
- (42) organic fertilizer consumption per hectare= 0.00759
Units: Ton/hectare
- (43) organic fertilizer use=cultivated land*organic fertilizer consumption per hectare
Units: Ton
- (44) per unit manure emission=4.5
Units: TonCO₂e/TLU/Year
- (45) population= INTEG (population growth,6e+06)
Units: Person
- (46) population growth=net population growth*population
Units: Person/Year
- (47) potential irrigable area=5.3e+06
Units: hectare
- (48) productivity=productivity due to fertilizer*productivity due to irrigation
*productivity due to organic fertilizer*productivity due to rain
fall*productivity due to technology *productivity due to

temperature *normal level of productivity

Units: Ton/hectare

(49) productivity due to fertilizer = WITH LOOKUP (chemical fertilizer per hectare/ref chemical fertilizer,([(0,0)-(10,10)],(4.8e+06,1),(6e+06,1.06),(1.48e+07,1.256),(9.6e+07,1.14)))

Units: 1

(50) productivity due to irrigation = WITH LOOKUP (irrigation/ref irrigation,([(0,0)-(10,10)],(9.6,1.05),(4.8e+06,0.95),(6e+06,0.99),(1.48e+07,1.14),(2e+07,1.237),(3e+07,1.4),(4e+07,2)))

Units: 1

(51) productivity due to organic fertilizer = WITH LOOKUP (organic fertilizer consumption per hectare/ref organic fertilizer,([(0,0)-(10,10)],(4.8e+06,0.95),(4.8e+06,0.99),(9.6e+06,1.05),(1.48e+07,1.14),(2e+07,1.237),(3e+07,1.4),(4e+07,2)))

Units: 1

(52) productivity due to rain fall = WITH LOOKUP (rainfall/ref rainfall,([(0,0)-(10,10)],(300,1),(400,1.02),(500,1.05),(700,1.09),(1000,1.12),(1300,1.14),(1600,1.15)))

Units: 1

(53) productivity due to technology = WITH LOOKUP (investment in technology/ref in technology,([(0,0)-(10,10)],(4.8e+06,0.95),(6e+06,0.99),(9.6e+06,1.05),(1.48e+07

,1.14),(2e+07,1.237),(3e+07,1.4),(4e+07,2))

Units: 1

(54) productivity due to temprature = WITH LOOKUP (temprature/ref temp,([(0,0)-(10,10)],(10,0.8),(12.5,0.95),(17.5,1.05),(22.5,1.2),(27.5,1.3),(30,0.85)))

Units: 1

(55) rainfall=average rainfall*rainfall due to GHG concentration

Units: mm

(56) rainfall due to GHG concentration = WITH LOOKUP (GHG concentration/ref for GHC, ([[(0,0)-(10,10)],(1e+08,0.08),(2e+10,1.12),(5e+10,1),(1.5e+11,0.5),(2e+11,0.4),(3e+11,0.33)])

Units: dmnl

(57) ref chemical fertilizer=1

Units: Ton/hectare

(58) ref for GHC=7.21934e+10

Units: TonCO2e

(59) ref in technology=1

Units: birr

(60) ref irrigation=1

Units: hectare/Year

(61) ref organic fertilizer=0.00759

Units: Ton/hectare

(62) ref rainfall=1

Units: mm

(63) ref temp=25

Units: Celsius

(64) SAVEPER =TIME STEP

Units: Year [0,?]

The frequency with which output is stored.

(65) temperature=effect of GHG on temprature+normal temperature

Units: Celsius

(66) TIME STEP = 10

Units: Year [0,?]

The time step for the simulation.

(67) time to dispose emission=15

Units: Year

(68) total fertilizer use=chemical fertilizer use+organic fertilizer use

Units: Ton

(69) total forest area converted to agricultural land= forest land*fraction of land converted to agricultural land

Units: hectare

(70) total land area=1.1043e+08

Units: hectare

2 Appendix B Historical data

Year	Cultivated land in sq.km	GHG Emissions (Tonnes)	Population(person)
2000	305590	71,000	67,031,867
2001	304980	74,000	69,018,932
2002	316070	83,000	71,073,215
2003	331010	81,000	73,168,838
2004	335910	83,000	75,301,026
2005	342190	86,000	77,469,940
2006	350770	91,000	79,691,050
2007	345130	100,000	81,996,185
2008	349850	104,000	84,357,105
2009	356830	108,000	86,755,585
2010	363252	112,000	89,237,791
2011	364880	111,000	91,817,929
2012	366990	116,000	94,451,280
2013	369100	120,000	97,084,366
2014	371210	126,000	99,746,766
2015	373320	129,000	102,471,895
2016	375401	135,000	105,293,228
2017	379030	138,000	108,197,950
2018	381900	148,724	111,129,438
2019	384761	159,695	114,120,594
2020	385950	167,300	117,190,911