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SUSTAINABLE CROP PRODUCTION IN ETHIOPIA: A SYSTEM DYNAMICS APPROACH

A RESEARCH SUBMITTED TO THE SCHOOL OF BUSINESS AND ECONOMICS IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTERS OF SCIENCE IN ECONOMICS (APPLIED ECONOMIC MODELLING)

BY: BIRUK GEBRETSADIK

ADVISOR: ZERAYEHU SIME (PHD)

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The work presented in this thesis is to the best of my knowledge and belief, original except as acknowledged in the text. I declare that I have not submitted this material, either in full or in part, for a degree in this or any other institution. No part of this work should be copied, either in part or full, without my permission and that of Addis Ababa University. Signed___________________ date_______________

Biruk Gebretsadik

GSR/9777/14

Department of Economics

This is to certify that the thesis prepared by Biruk Gebretsadik, entitled: Sustainable Crop Production in Ethiopia: A System Dynamics Approach and submitted in partial fulfillment of the requirement for the degree of Master of Science (Applied Economic Modeling) compiles with the regulations of the University and meets the accepted standards with the respect to originality and quality

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Abstract

This study discusses how to transform the current crop production system in Ethiopia into a sustainable way of production. Since the current production system poses a danger to the environment and failed to meet the food demand of the growing population, the issue of sustainability arose. To solve the underlying socioeconomic problem of the sector, a holistic and integrated approach is needed. To do this a system dynamics approach is selected. A stock-flow diagram is built to capture the dynamic interaction that exists among social, economic, and environmental aspects of crop production. The model proved its robustness using various model validation tests. Land acidity as well as post-harvest loss, and loss due to incidence of pests and diseases are identified as a major bottleneck of the sector. To determine the leverage point at which the sector becomes sustainable, four scenarios were tested: increasing the share of improved seed relative to local seed; switching from inorganic to organic fertilizer; increasing irrigation area; and expanding agricultural extension services. According to the findings, increasing the use of improved seed and organic fertilizer has a significant potential to promote economic efficiency, social welfare, and environmental sustainability. The simulation's outcome demonstrates that using improved seeds increases productivity and decreases the prevalence of pests and diseases, leading to high crop yields and reduces undernourishment. Furthermore, extensive use of improved seed reduces the need to extend cultivated areas by clearing forests. In addition to increasing productivity, the use of organic fertilizer can lower the amount of greenhouse gases and acidity in the soil that can result from the use of chemical fertilizers. To address the demand for more cultivated land without causing more deforestation, extending irrigation areas was found an effective way to maintain the current level of forest cover. Increasing agricultural extension services reduces reducing post-harvest loss and increases crop production.

Key words: Crop production, Sustainability, Food insecurity, Greenhouse gas concentration, System dynamics, Ethiopia

List of Acronyms

CLD	Causal Loop Diagram
CO_2	Carbon dioxide
GHG	Greenhouse Gas
CSA	Central statistical Agency
FAO	Food and Agriculture Organization
FDRE	Federal Democratic Republic of Ethiopia
NBE	National Bank of Ethiopia
SFD	Stock and Flow diagram
WB	World Bank

Chapter One- Introduction

1.1 Background

During the 1960s, primarily developing countries faced a food crisis as a result of rapid population growth that outpaced crop production (Khush, 2001). Large-scale famine and hunger were expected (Conway, 2019). Fortunately, the green revolution began in India in the 1960s intending to increase crop production, reduce poverty and hunger, and promote food security, and quickly spread throughout the world (Abayechaw & Dikir, 2022). As a result of the green revolution, cereal production has outpaced population growth, with rice and wheat production in Asia increasing by 132% and 91%, respectively (Khush, 2001). A threefold increase in cereal yield and production had been recorded (P. J. Gregory & George, 2011).

But this success was short-lived, and again production has slowed and the issues of poverty, hunger, food insecurity, sustainability, greenhouse gas emissions, and environmental degradation have become global problems (Khush, 1999; Patel, 2013; Pingali, 2012). Many countries wrongly perceived that the problem of food production has been solved and the issue of food security is just a matter of distribution and market access. But this perception does not last long due to the 2008 global economic crisis. This crisis brings the question about the cost of the increase in crop production (P. J. Gregory & George, 2011). And the issue of sustainability become at the forefront of academic debate.

The traditional crop production system is unable to supply enough food for the world's expanding population. Undernourishment rates increase from 8% in 2019 to 9.8% in 2021. More than 800 million people are food insecure, and by 2021 there were about 2.3 billion individuals who are moderately or severely food insecure. In 2020, there were 22% of stunted children in the world, and 3.1 billion people were not able to afford decent food. FAO estimates that crop output has to increase by 60% in 2050 to meet the demands of the expanding population(WFP & UNICEF, 2022).

Furthermore, crop production's expansion came at the expense of the environment. Globally, agriculture was responsible for the emission of 9.3 billion tons of CO_2 equivalents in 2018. Methane and nitrous oxide emissions from crop cultivation and animal sectors have increased by 14% since 2000. One-third of agricultural emissions are contributed by the sector that produces crops. Application of synthetic fertilizer in particular releases N2O, which made about 13% of all agricultural emissions (0.7 Gt CO2eq) (Tubiello et al., 2021).

There are signs of unsustainable crop production in Ethiopia. According to FAOSTAT, the number of individuals who are undernourished reached 28.6 million in 2020. Crop production emits greenhouse gases, which is one of the causes of climate change. Additionally, because of climate change, it is the most susceptible sector. The third greatest source of greenhouse gas emissions in Ethiopia is crop agriculture. Numerous initiatives are being made to achieve sustainable development, to accelerate economic growth while also addressing societal and environmental problems at the root of the problem. The Ethiopian government is putting into action a national adaptation strategy to build a climate-resilient green economy from 2019 to 2030 to enhance crop production to solve the problem of food insecurity, lower damaging environmental effects of crop production, and lessen vulnerability to climate change (Ethiopia, 2019). An in-depth analysis of the extensive impact of crop production will be done in this study, taking into account social, economic, and environmental factors in an integrated and holistic manner.

The purpose of this study is to build a system dynamics model to identify the main factors preventing crop production from being sustainable and to analyze policies to find the highest leverage point at which the industry can become economically profitable, socially desirable, and environmentally friendly.

1.2 Problem statements

Ethiopia's economy is heavily reliant on agriculture, which employs 72.7% of the labor force, accounts for 32.7% of GDP, and accounts for 70% of export earnings in 2019/2020. Crop production is the most important subsector of agriculture, accounting for 65% of agricultural GDP and growing at a 6.1% annual rate (Planning and Development Commission, 2021). Despite the fastest growth in crop production in recent years, it has faced several challenges in terms of sustaining growth. Its performance was not only inadequate to meet the needs of a growing population, but it was also hazardous to the environment.

For the past few decades, crop output in Ethiopia has been on the upswing. However, neither the economy nor society found this advancement satisfactory. Given the level of technology in use today, crop production has the potential to enhance yield by 24%. The post-harvest loss of crops is a significant problem that prevents agricultural production from producing the required yield for consumption. For instance, the postharvest stage saw losses of 8.43 percent, 10.51 percent, 14.26 percent, and 17.49 percent of the production of maize, wheat, faba beans, and haricot beans, respectively (FAO, 2023). The incidence of undernourishment was influenced by ineffective agricultural production, post-harvest loss, and other hindrances. 56.2% of Ethiopia's population currently experiences moderate to severe food insecurity, according to an FAO assessment from 2022. The number of persons who are undernourished doubled from 2016 to 2020. 5.5 million People experienced acute food insecurity in 2021, while 353,000 are in a disaster, 3.1 million in a crisis, and 2.1 million experienced an emergency (IPC, 2021).

In addition to not being able to meet the increasing population's need for consumption, it is becoming a greater burden for the environment. The extension of agricultural area, which results in a reduction in forest land, is what led to the observed growth in crop production. For illustration, in 2020–21, the production of grain and pulses grew by 1.8 and 6.5%, in part due to an increase in cultivated land of 0.6 and 7.1%, respectively while the output of oilseeds decreased by 7.7% due to a decrease in cultivated land (National Bank of Ethiopia, 2020/21).

Through its emissions, crop production is a significant contributor to climate change, and also, it is the industry that has been most susceptible to climate change. It is the third largest source of Greenhouse gas emissions in Ethiopia mainly due to the application of chemical fertilizer, which accounts for 58% (FDRE, 2011). Chemical fertilizer application makes the acidity of the land worse; at the moment, around 40% of arable land is damaged (Sori, Iticha, & Takele, 2021). About 62% of new cropland comes from forest land and about 50% of greenhouse gas emissions from forestry were driven by deforestation for agricultural land (FDRE, 2011). Eshete, Mulatu, and Gatiso (2020a) assert that CO_2 emissions harm agricultural productivity in general, and especially crop productivity. Climate change becomes a cause of rainfall shortage and exacerbates the incidence of pests and diseases. For instance, in 2023, 11.21 percent of maize, 9.12 percent of wheat, and 15.78 percent of faba bean were lost due to climate change. It was caused by about 46% due to a shortage of rainfall, followed by antimicrobial diseases and anti-crop pests (12.8 percent) and (11.9 percent) respectively (FAO, 2023).

There have been different studies conducted so far regarding the economic, social, and environmental effects of crop production. Most studies focus on enhancing crop productivity to achieve food security (Adenew, 2004; Pawlak & Kołodziejczak, 2020), while others examine the adverse effects of crop production on the environment(P. Gregory et al., 2002; Hakeem, 2015). There are also a lot of studies that demonstrate the impact of climate change on crop production (Asfew & Bedemo, 2022; Deressa & Hassan, 2009; Hagos, Lunde, Mariam, Woldehanna, & Lindtjørn, 2014; Solomon, Simane, & Zaitchik, 2021; Wubie, 2015). However, they barely understand the complexity of the issue.

To achieve the path toward a sustainable way of production in Ethiopia a planned and coordinated intervention is needed. Crop production systems are made up of multidimensional components that are intricately linked (Walters et al., 2016). To achieve a sustainable way of production a systematic assessment of the whole crop production system is needed rather than considering the components independently. Therefore, this study employed a system dynamics approach to understand the complex, nonlinear, and dynamic nature of crop production system. A system dynamics model enable us to understand the systematic and dynamic interactions that exist among economic, environmental, and societal component of crop production to achieve a more sustainable system of production.

1.3 Objective

1.3.1 General objective

The general objective of the research is to examine the complex and dynamic interaction that exist among social, economic, and environmental component of crop production in Ethiopia.

1.3.2 Specific Objective

- To demonstrate the feedback interaction and interdependence that exists between crop production's economic, environmental, and societal components.
- To critically determine the sector's sustainability-impediment factors.
- To determine whether the industry can achieve sustainable development under business as usual scenario.
- To identify the highest leverage point at which crop production becomes sustainable.

1.4 Research Questions

1. What kind of policy intervention has the potential to achieve a highest leverage point where the sector becomes sustainable?
2. How do systemic and dynamic interactions between economic, social, and environmental factors affect sustainability?
3. What are the potential factors that make the sector unsustainable?
4. Can the industry be sustained with the current system of production?

1.5 Scope of the study

The study only covers Ethiopian crop production practices and experiences. A time series data from 2000 to 2020 was used to make a comparison between the behaviors of a real system with the simulated model behavior. It will concentrate on examining crop production from a sustainability perspective. Among various indicators that show the well-being of society, food security was selected to investigate the societal implication of the sector. The amount of yield produced was used to show the economic efficiency of the sector. Forest cover and Greenhouse gas concentration caused by the application of agricultural input and their environmental impact were used to demonstrate the environmental dynamics of the system.

1.6 Significance of the study

This study has huge significance both for academicians and policy makers. First, by using system dynamics to comprehend the socioeconomic issues related to agricultural production, we can pinpoint the major sustainability hindrances. Additionally, the study's use of the system dynamics approach helped us come up with effective and superior policy alternatives to guarantee sustainable agricultural production. Since the majority of Ethiopians depend on rain-fed agriculture, which is incredibly vulnerable to climate change, this study also helps with efforts to combat climate change. Since this study was in line with climate resilient green economy strategy and the Ten years development plan, it will contribute a lot to policy makers. Additionally, the topic's novelty will pave the way for the next academician. Any academic or professional who is interested in the topic of sustainability can use it as input.

1.7 Organization of the study

This study has five chapters. The first chapter includes the background of the study, a statement of the problem, major and minor objectives, research questions, the scope of the study, and the significance of the study. The definition of the topic, an overview of crop production and its relationship to food security, a theoretical literature review, and an empirical review are all covered in chapter two. The methodological part is discussed in chapter three. Model validation in chapter four, conclusion, and major findings discussed in the last chapter.

Chapter Two - Literature review

2.1 Definition and concepts

Sustainable crop production per Sassenrath et al. (2009) is an approach that produces crops in a way to increase the profitability of rural farmers, uses on-farm resources efficiently to reduce harmful impact on the environment and people sustains the natural productivity and quality of the land, and water to ensure food security. Crop production should satisfy the social, economic, and environmental needs to be sustainable. Sustainable crop production must enhance better life for the farmers and supply societal needs, conserve and maintain the environment and natural resources, and increase the amount of yield produced.

Sustainable crop production increases the amount of crop produced and the economic gain of it without adversely affecting the environment and quality of crops. It enables the system to maintain food stability without further need and use of chemical inputs. Sustainable crop production enables the achievement of food security, using organic fertilizers, reducing the application of chemical fertilizers and pesticides, keeping the soil rich with organic matter, and protecting the environment and biodiversity. Sustainable crop production contributes to a reduction of greenhouse gas emissions and carbon footprint. Sustainably produced crops are highly preferred and important for consumption because of their high organic content as compared to commercial crops (Imadi, Shazadi, Gul, & Hakeem, 2016).

Crop production to become sustainable it should be economically, socially, and environmentally viable. Various research studies show the unsustainability of the underlying crop production system in Ethiopia. An increasing challenge from climate change, unsustainable use of agricultural chemical inputs, increasing trend of emission from crop production, and the inability of crop production to feed the growing population are some indicators that demonstrate the unsustainability of conventional production systems. In this section, we will review various works of literature and research findings of different scholars.

2.2 Empirical studies

Numerous studies have been conducted on the challenges and opportunities facing the sector, as well as the impact that crop production has on the economies and social well-being of the nations.

Some studies revealed that crop production become a mainstay of the countries' economy and societies' well-being. Using a recursive household food security model, Feleke, Kilmer, and Gladwin (2005) found that supply-side variables such as using improved technologies and inputs are more powerful determinants of food security in southern Ethiopia. However, population pressure, drought, and land degradation become major constraints to crop production that hamper the state of food security (Mohamed, 2017).

Bufebo and Elias (2021), used remote sensing data, field observation, household survey, key informant interviews, and focus group discussions to identify drivers and consequences of land use/ land cover change in the Shenkolla watershed in southern Ethiopia. The outcome of the finding demonstrated that agricultural land expansion become a major driver of land use/ land cover change, which in turn hampered the amount of crop production. Using remote sensing and participatory field point sampling, Garedew, Sandewall, Söderberg, and Campbell (2009) found that cropland doubled at the cost of woodland and wooded-grassland in central Ethiopia rift valley from 1973-2006. Kindu, Schneider, Teketay, and Knoke (2015), who used GIS-based analysis and regression, also found that the expansion of cultivated land is one of the top six drivers of land use land change. Based on remote sensing, field observation and information from local people, Tolessa, Dechassa, Simane, Alamerew, and Kidane (2020) found a fold increase in size of cultivated land and fivefold expansion in area of commercial farm contributed significantly to decline in the size of wetland, shrub land, grassland, and forest land in Didessa sub-basin of Blue Nile. An increase in land use change coupled with climate change poses an alarming threat to a crop production system.

The finding of Bastan, Khorshid-Doust, Sisi, and Ahmadvand (2017), who used system dynamics simulation approach find that the required water and profit gained from agriculture are the major determinant of the development of the agricultural sector in Damavand city, in Iran.

However, shortage of water becomes a major constraint, for which water saving policy is important to bring agricultural development. Using a Ricardian model to analyze the impact of climate change on the performance of crop production around the Nile basin of Ethiopia, Kassahun (2009) found that an increase in temperature and decline in precipitation adversely affect agricultural productivity, especially in dry farm lands. Expanding irrigated lands was recommended as an efficient and better adaptation mechanism for climate change.

By using a recursive dynamic computable general equilibrium model to explore the impact of CO2 emission on agricultural performance and household welfare, Eshete et al. (2020a) found that an adverse impact of CO2 emission on agricultural productivity and households welfare, particularly traded and nontrade crop production affected severely. According to Tadesse, Tilahun, Bekele, and Mekonen (2021) low supply and application of improved seed varieties and fertilizers, soil acidity, low extension service, diseases and insect pest, and conflict are the main bottleneck of crop production.

Even though several challenges impended crop productivity, still there are opportunities to overcome such challenges. Using a meta-analysis of economic efficiency in crop production, Bati (2020) revealed crop production still has the potential to increase the amount of yield by 24% or to reduce the cost by 53 percent given the existing level of technology and resources. A study made by Hiwot (2020) in Woliso Woreda found that using climate-smart practices such as fertilizer use and water and soil conservation on average produces 61% more yield compared to without climate-smart practices. By applying a retrospective-cross-sectional study in Hidhabu Abote Woreda, Also Dawit (2007), who utilized the logit model to determine the impact of soil conservation on crop productivity in southern Ethiopian highlands, found a positive relationship. However Tessema (2011) found a negative relationship between soil and water conservation and crop production in the northern highland of Ethiopia by adopting propensity score matching (PSM), and endogenous switching regression methods. Nazrawit (2019) demonstrates that the application of climate-smart practice has the potential for crop productivity and ensuring food security. However, According to Shi and Gill (2005)-who used the system dynamics model to develop effective policy measures to facilitate sustainable agricultural development - asymmetrical information access, the risk aversion nature of farmers, and high transaction cost are identified as major barriers to implementation of alternative practices. Campbell, Myers, and

Curtin (1995) found that the application of sustainable agricultural practice is more affluent and better positioned in temperate ecosystems relative to the tropics. This is due to most farmers in the tropics being subsistence, which gives priority to immediate economic gain rather than protection of the environment.

Walters et al. (2016), used qualitative and quantitative data to simulate a system dynamics model to evaluate the role of economic, social, and environmental drivers in determining the difference in sustainability between livestock-only, crop-only, and integrated crop and livestock systems. The result from this simulation effort revealed that the crop-only production system has the greatest potential for sustainability relative to others.

These findings indicate that the current crop production system is unsustainable which poses a danger to the environment, as well as economically inefficient and socially unable to meet the demand of the growing population. From this review of previous literature, it is evident that existing studies focus on analyzing the contribution of the sector to the national economy, and in determining its challenges and opportunities. However, these studies are not able to integrate all factors and dimensions and are unable to provide comprehensive analyzes of the problem. It needs an integrated and holistic approach to understand the problem and to provide effective policy intervention. In this study system dynamics approach will be utilized to develop a better crop production system that maximizes socioeconomic gains, while reducing its adverse consequence on the environment.

2.3. Overview of crop production in Ethiopia

The agricultural sector dominates the Ethiopian economy for decades in terms of foreign exchange earnings, employment, share of GDP, and raw material supply. Despite COVID-19 and instability in the Northern part of Ethiopia Agriculture grew in 2020/21 by 5.5%, larger than in previous years mainly due to an increase in crop production (National Bank of Ethiopia, 2020/21)

Agriculture comprises crop production and livestock subsector. Crop production is the largest sub-sector that takes the lion's share accounting for 65.1% of agricultural GDP (20% of total GDP) and five of the top six export commodities by share (National Bank of Ethiopia, 2020/21). Small-scale subsistence farming is the predominant farming practice that uses 95% of the total cropland area and participates in 8 million households accounting for more than 90% of total agricultural production (FDRE, 2011).

Indigenous and diversity of various crops found in Ethiopia. Meher(main) season from September to February and Belg season crop harvested from March to August, are the two important crop harvesting seasons in Ethiopia. Crop production includes cereals, pulses, oil seeds, chat, coffee, root crops, herbs, vegetables, flowers, fruits, and sugar cane which are produced for food, preparing beverages, stimulation, and making clothing. In 2020/21 total grain production reached 341.8 million quintals of which cereal production accounted for 88.3% followed by pulse and oil seed which account for 9.4% and 2.3% respectively. Maize, Wheat, Teff, and Sorghum together accounted for 87.2% of total cereal production in 2020/21 (C. S. A. CSA, 2021).

Despite recent noticeable advancements in crop production, given current levels of technology and resources, there is still huge potential for yield increases of 24% or cost reductions of 53% (Bati, 2020). To effectively utilize crop production, various strategies, and policies have been adopted. For instance, Ethiopia aimed to reach middle-income status by 2025, according to GTP. The agricultural sector is expected to grow at an 8.6% rate to meet this goal. In turn, this necessitates an increase in crop productivity from 19 quintals per hectare to 22 quintals per hectare. Major food crops like Teff, wheat, and maize, are planned to increase from 19 million tonnes to 27 million tonnes (FDRE, 2011).

According to The development and planning commission, the current government of Ethiopia intended to implement home-grown economic reform and has proposed a ten-year development plan with the slogan "pathway to prosperity" for the years 2021 to 2030. A resilient green economy, quality economic growth, shared prosperity, and increased economic productivity and competitiveness were the goals of the homegrown economic reform. The Ethiopian economy is expected to grow 10% annually over the next ten years. To achieve a 10% annual average growth rate of GDP, crop production must increase at a rate of 4.6% annually, and the agricultural sector is anticipated to grow at a rate of 5.9% annually. The primary goals of the agricultural development plan are to increase farmer income and quality of life, generate enough jobs in rural areas, eradicate poverty, meet the food needs, supply raw materials to other industries, increase the amount of exportable agricultural products by raising yields, and develop climate-resilient and organic crop production (FDRE, 2011).

2.3.1 Agricultural inputs and environment

Application of chemical fertilizer is sharply increasing to boost agricultural productivity to meet the fiber and food demand of the growing population over all the world (C.S. Snyder a, *, T.W. Bruulsema b, T.L. Jensen c, P.E. Fixen d 2009). As one of the most populous countries in the world, Ethiopia has faced the challenge of feeding the growing population. Different policies have been implemented to combat this growing food insecurity. For instance, during 1993 the Sasakawa/Global 2000 Program (SG) and the Ministry of Agriculture (MOA) launched a joint program (Howard et al., 1999). As a result of the program, fertilizer imports increased from 47 000 tons in 1993 to 137 000 tons in 1996. Following this massive application of chemical fertilizer, Ethiopia recorded one of the highest harvests of major crops in history in 1995/96 and 1996/97 (Quiñones, Borlaug, & Dowswell, 1997).

To address food insecurity and vulnerabilities, the Ethiopian government is making significant efforts and investments to boost agricultural productivity. For example, to boost the productivity of major crops (254 million quintals), 1.23 and 9.23 million quintals of improved seeds and fertilizer were used respectively in 2012/13 (FDRE, 2011). This extensive application of chemical inputs has an adverse impact on the environment. In 2010, crop production emits 12

MtCO2e, of which the use of chemical fertilizer accounts for 58% (FDRE, 2011). Over use of chemical fertilizers also cause soil acidity, which affects around 43% of Ethiopia's arable land (Haile et al., 2017). Moreover, extensive use of fertilizer and pesticides intensifies land degradation, which affects the Ethiopian agricultural sector severely by reducing soil fertility (Abebaw, 2019).

This increasing use of chemical fertilizers and pesticides has increased greenhouse gas concentration in the atmosphere, this concentration of GHG results in climate change which in turn affects crop production adversely. Various studies demonstrate that climate change is posing an increasing threat to agricultural productivity. According to Kassahun (2009) increases in temperature and decline in precipitation are adversely affecting agricultural productivity, especially in dry farmlands. According to Eshete, Mulatu, and Gatiso (2020b), CO2 emissions reduce traded and non-traded crops as well as worsen the welfare of the societies.

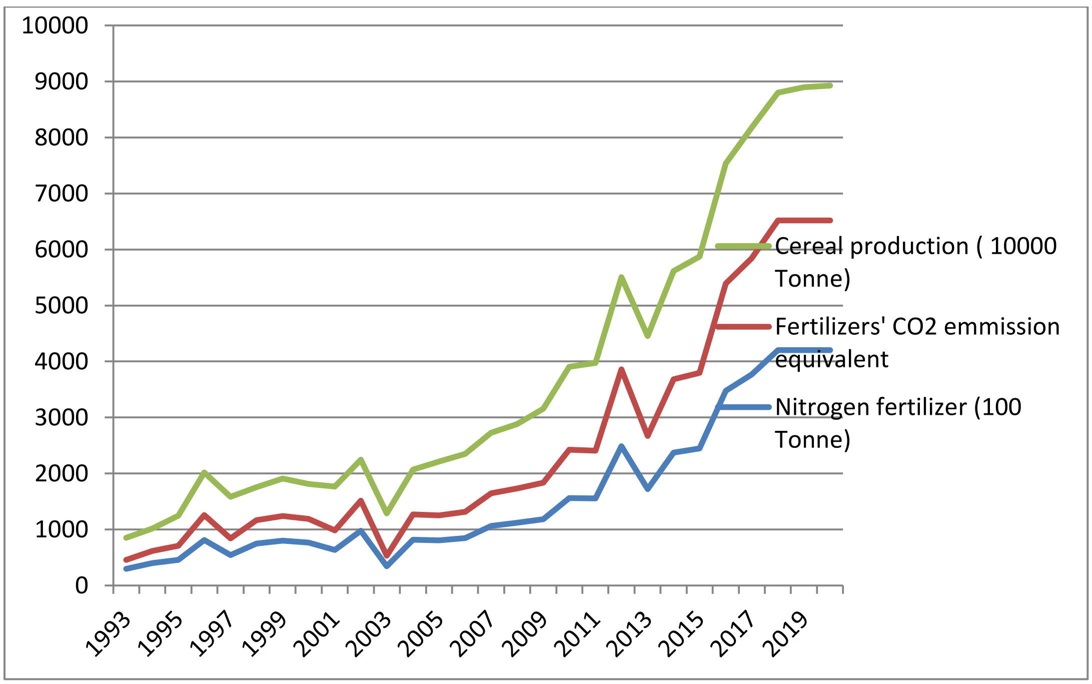


Figure 2.1: Trend for Nitrogen fertilizer, Cereal production, and Fertilizer's CO2 emission.

Source: FAOSTAT

The above graph clearly shows that an expansion in cereal production has been accompanied by extensive application of chemical fertilizers. Starting from the joint program of Sasakawa/Global

2000 Program (SG) and the Ministry of Agriculture (MOA), the application of chemical fertilizer shows an upward trend on average. An increase in chemical fertilizers results increase in cereal production on the one hand and raise CO2 emission on the other hand. The Green Economy Strategy predicts emissions from crop production will reach 60 MtCO2e by 2030 (FDRE, 2011).

2.3.2 Crop Production and Land cover change

The conversion or modification of an existing land cover into a new land cover type is known as land use change (Melese, 2016). The change in land cover is significantly influenced by human activity and social factors. There are underlying causes and proximate causes of the major changes in land cover. While proximate causes are human manifestations that can be seen through direct human action, underlying causes are the root causes that compelled people to intervene in land use change activity. One of the proximate causes of land cover change is the expansion of crop production (Geist & Lambin, 2002).

Cultivated cropland is sharply increasing over four decades at the cost of forest and glass lands According to Million (2002) land degradation was highly exacerbated mainly because of the policy of achieving food self-sufficiency via boosting crop production in south western Ethiopia. Between the periods of 1973 to 2000, the expansion of cultivation land was the main reason for 83.4% and 70.1% of vegetation loss in Abijjata Shala Lakes National Park and Zeway-Awassa Basin respectively (Muzein, 2006). Land cover change is the main driver of environmental change that in turn negatively affects crop production (B. Turner, Meyer, & Skole, 1994). It causes the degradation of forests that causes soil erosion and reduces land productivity which results in a low amount of production.

According to Bufebo and Elias (2021), agricultural land expansion is an important driver of land use/ land cover change in the Shenkolla watershed in southern Ethiopia. Between 1973 and 2017 forest land declined from 29.51% to 20.52%, while agricultural land increased from 70.49% to 79.48% in the same area. Teka, Van Rompaey, and Poesen (2013) indicated that the imperial and Derg regime’s land policies become a main contributor to the increase in cultivated land at the expense of vegetable land. Garedew et al. (2009) found that cropland doubled at the cost of woodland and wooded-grassland in central Ethiopia's rift valley. From 1976 to 1986, the cover of woodland declined from 40% to 9% in one of the study areas, while in another study area, 54% of woodland cover was lost. According to Kindu et al. (2015), expansion of cultivated land is the second highest driver of land use land cover change. From 1973 to 2012, Crop land increased by 271% in Munessa-Shashemene. The study conducted in the Didessa sub-basin of the Blue Nile, of Ethiopia by Tolessa et al. (2020) shows that decline in the wetland by 97.5%, grass land by 76%, forest land by 50.6%, and shrubland by 38.2% by four decades (1974–2014) due to increase in the area of cultivated land by more than a fold (44.2%), Commercial farmland expanded fivefold (414.4%). For Melese (2016) absence of applicable policy, intervention is cited as a main source of deforestation.

Even though the application of improved agricultural inputs increased starting from the 1990s to boost crop productivity, land extension remains the primary factor that determines the amount of crop production. Crop production is highly related to land extension. For instance, from 2005 to 2010 Ethiopian economy achieve double-digit economic growth (11%). During these years agricultural land expanded by 15% and resulted in a 40% yield increment in the agricultural sector was the main contributor to the double-digit growth (FDRE, 2011). During 2020/21 cereal and pulse production registered 1.8 and 6.5% growth rates partly because of the expansion of cultivated land by 0.6 and 7.1 % respectively, while oilseed production declined by 7.7% due to a decline in cultivation land. The total cultivated cropland area reached 13.0 million hectares, of which cereals production accounted for 81.2 percent, followed by pulses and oil seeds which accounts for 12.9% and 5.9%. Maize, Wheat, Teff, and Sorghum together accounted for 85.7% of the total cultivated area for cereal production in 2020/21 (National Bank of Ethiopia, 2020/21).

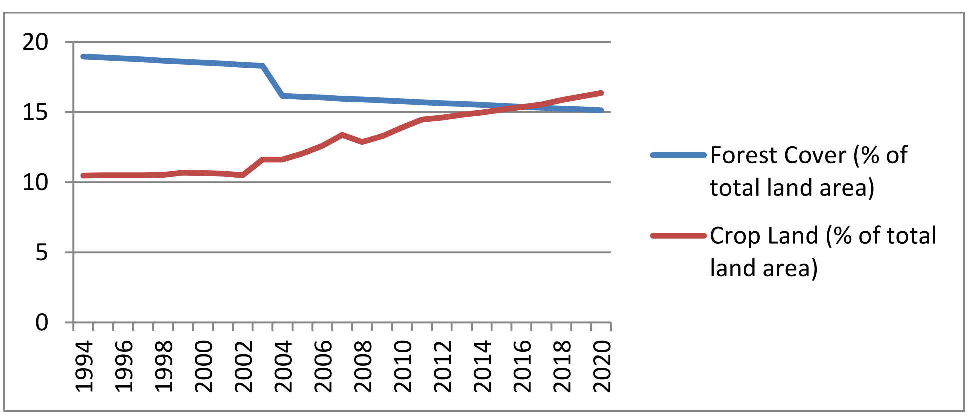


Figure 2.2: Trend for Share of forest land and Crop land

Source: FAOSTAT (2022)

The above graph shows a sharp increase in the share of crop land at the expense of forest land. During 1994, about 18,966.500 hectares or 18.97% of Ethiopia's land was covered by forest, this amount declined to 17,068,500 or 15.12%. While the amount of crop land rise from 10.472,000 or 10.47% to 18,476,100 or 16.57% between 1994 and 2020. Forest area annually decline at the rate of 0.40% during 2010, this rate slightly rise to 0.42% in 2020.

2.3.3 Crop production vs. food security

Food security refers to physical and economic access to sufficient and nutritious food which meets the food preferences of all people, at all times for an active and healthy life. If there is no either physical or economical access to nourishment at the individual or national level, we can say there is food insecurity (Mohamed, 2017). Even though the majority portion of the population engaged in crop production, many peoples undernourished or get lower than the required amount of food. Ethiopia is severely affected by food insecurity for centuries (Ayenew, 2013)

Food security poses a major challenge to Ethiopian crop production. Even though crop production increased at a steady rate, it was unable to feed the growing population of Ethiopia. The main indicator is the prevalence of undernourished people. Food inflation is another indicator of the prevalence of food insecurity. It increase from 7.2% in 2016/17 and reach 23.2% in 2020. It was higher than the general level of inflation which was 20.2%, while food inflation was 23.2% in 2020 (National Bank of Ethiopia, 2020/21). Since Ethiopia's crop production is highly dependent on rainfall, it makes it vulnerable to the impact of climate change. Drought and land degradation are major determinants of food insecurity in Ethiopia (Hamza & Iyela, 2012; Mohamed, 2017). According to Feleke et al. (2005), supply-side variables like the amount of crop produced are more important determinants of food security than demand-side variables.

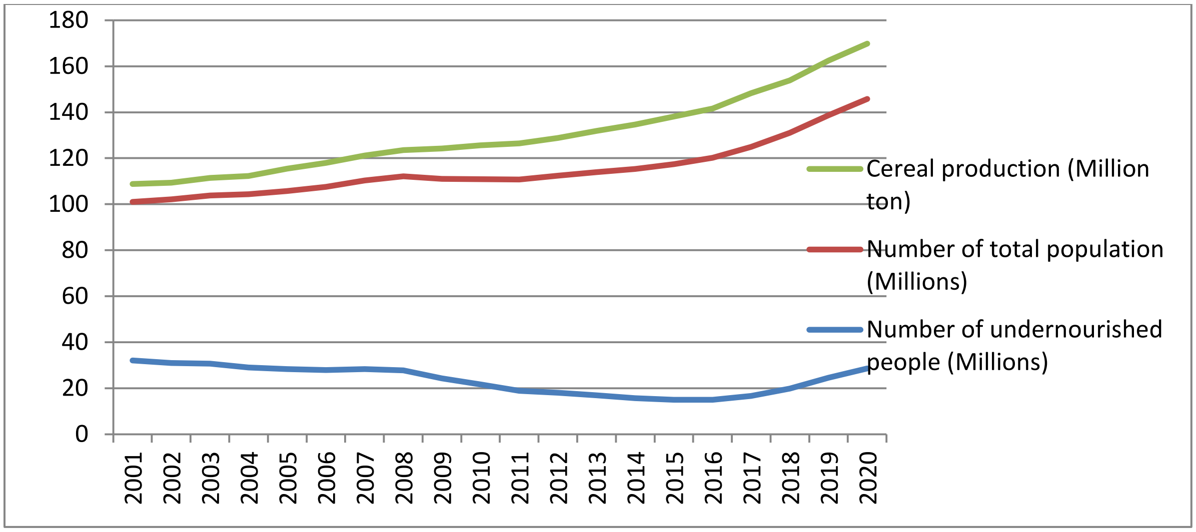


Figure 2.3: Trend for Population, number of undernourished people, and Cereal production.

Source: FAOSTAT (2022)

The trends in cereal production and total population show a consistent upward trend, while trends in undernourished people slightly reduce for consecutive years but later start to rise. After 2015 number of undernourished people increase at an alarming rate, this is due to the 2015 El Niño drought which is one of the most severe droughts in Ethiopia's history. In recent years the number of undernourished people is increasing along with the increase in population. The growth rate of undernourished people outpaced the growth rate of crop production. For instance, in 2020 undernourished people grow by 16.2%, while cereal production grows only by 1.3%. Surprisingly the growth rate of the population (2.6%) outpaced the growth rate of cereal production (1.3%) in 2020. Currently, 28.6 million people are undernourished in Ethiopia.

2.4 Conceptual framework

Based on the review of relevant pieces of literature, the following conceptual framework was developed. It shows that application of agricultural inputs has both direct and indirect effect on crop production. In one hand chemical inputs boost productivity and production while on the other hand they contribute for GHG concentration and causes climate change which adversely affect production. Food insecurity determined by the performance of crop production and population level. It occurred when crop production fails to feed the population. Crop production is also a driver of and vulnerable to climate change. Prevalence of severe food insecurity is main driver for conversion of forest land to cultivation land. This conversion fasten deforestation rate which become main cause for GHG concentration.

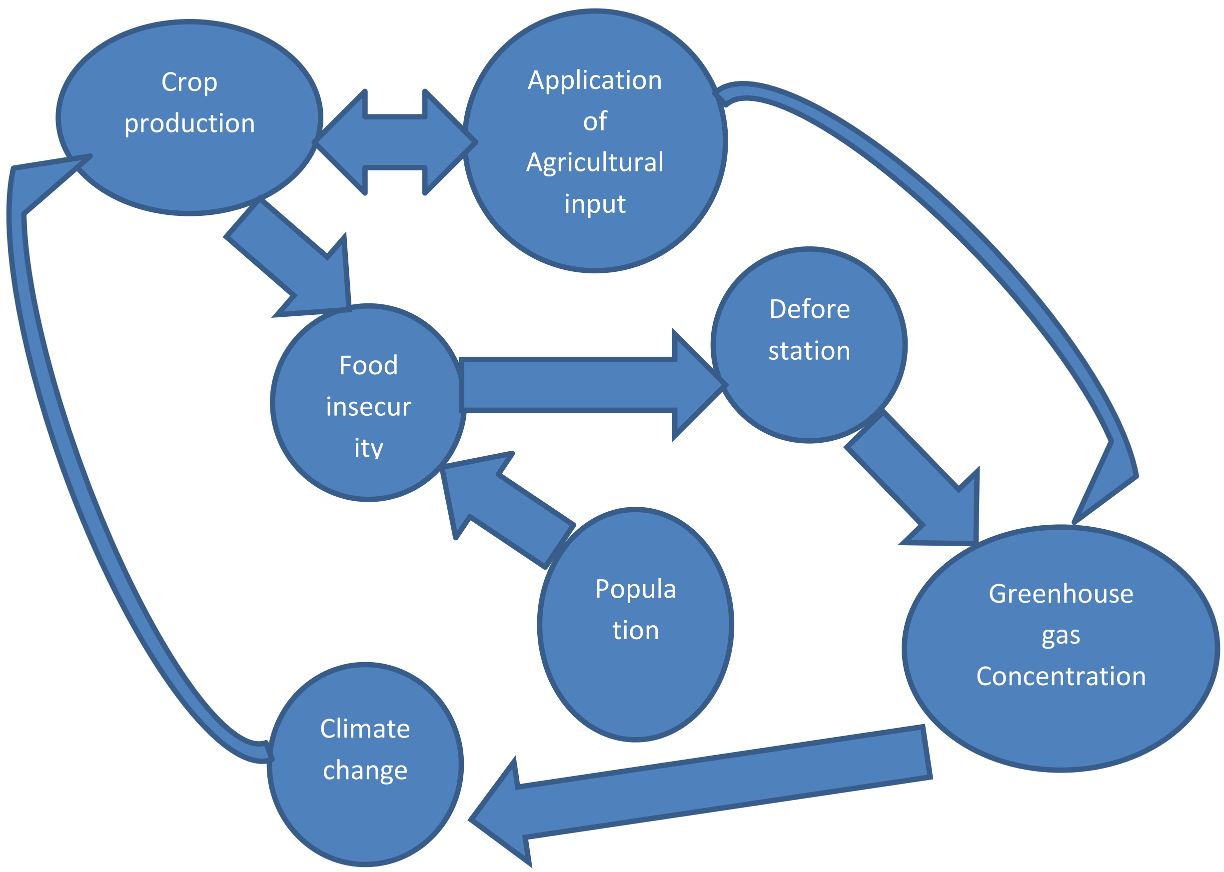


Figure 2.4: Conceptual framework

Chapter Three – Research Methodology

3.1 Data Sources

To make crop production environmentally, socially, and economically feasible and able to fulfill the rising demand of the present and future generations, a system dynamics model has been created. This model aims to capture the interaction and dependency that occur between different components of crop production. To build this model, a thorough examination of the literature on crop production, how it interacts with the environment, and its empirical impact on the incidence of undernourishment and greenhouse gas concentration in the context of developing nations was conducted.

To completely understand the problem, significant amounts of data are required due to the system's complexity. The data base for this dynamic model is composed of numerical, written, and mental information. Experts' expertise and experience in the field of crop production are viewed as a mental data bank. Understanding historical behavior is crucial for creating the model's framework (Andersen et al., 2007). Input from individual private conversations regarding crop production and its relationship to the environment was used to help conceptualize the model.

Journal articles, books, reports from government agencies, and other written data sources are all included. They were employed to enhance the comprehension of the model and provide the framework for the causal loop diagram. Written data bases are also required for the development of equations and model validation. The academic works of literature and reports of organizations like CSA, NBE, FAO, and UN agencies were used to gather the qualitative data that formed the basis of the model. The secondary data, which is used as an input for the initial value of stock variables and parameter values, is known as a numerical data base. The quantitative data needed for the construction of the stock flow diagram is taken from public institutions databases such as the Central Statistical Agency of Ethiopia (CSA), the statistical division of the Food and Agricultural Organization of the United Nations (FAOSTAT), and the World Bank.

3.2 Approach

A system dynamics approach was used in this study to simulate the available data. A review of the available literature, the findings of the study, and brainstorming were used to develop the problems. A causal loop diagram is used to show the interdependence and feedback within the crop production system. Vensim simulation software was used to create a Stock Flow Diagram to carry out technical analysis. The system dynamics approach makes it possible to examine the dynamics of crop production systems as well as to pinpoint the best opportunity for policy changes. This holistic framework that evaluates all system components is well suited to addressing complex problems associated with economic, social, and environmental components of crop production because of their cross-disciplinary and intricate nature (Pham, Reardon-smith, & Deo, 2021).

Since Jay Forrester created the concept of system dynamics in 1959, it has found use in a variety of contexts, including the modeling of intricate environmental and economic systems (Costanza & Voinov, 2001). Because it can address the incapability of static and linear models to include dynamic interactions of components in complex systems, this methodology was chosen for this study (J. Sterman, 2000). Causal loop diagrams (CLD), a type of qualitative modeling that illustrates the interrelations of systemic factors; and Stock flow diagrams, a type of quantitative modeling that represents and simulates dynamic interactions of factors (Luna- Reyes & Andersen, 2003).

Although system dynamics have some limitations in terms of model validation, modeling experts argue that model validity should be evaluated based on its usefulness for the objective (Yaman Barlas, 1996b). The primary goal of using system dynamics was not to obtain the correct answer, but rather to gain useful information by participating in the modeling process itself.

First, to hypothesize the preliminary structure of the model, an intensive literature review was done to understand systemic interactions in a crop production system. Then, by using this information, CLD was developed to depict feedback interactions of components in the system. This CLD was used to develop the structure of the Stock Flow diagram, which parameterizes and simulates using data. After the model stock and flow diagram is constructed, model validation tests and policy analysis had done.

3.3 Dynamic Hypothesis

The performance of Crop production in Ethiopia shows a positive trend for the last decades. But it was unable to feed the growing population of Ethiopia and resulting in food insecurity(Ayenew, 2013). The prevalence of undernourishment is taken as an indicator of food security. The prevalence of undernourishment necessitates the conversion of forest land to cultivation land(Cerri et al., 2018), which has a counterbalancing effect. On one hand, the expansion of cultivation land led to higher crop production(Barbier, 2004) and a lower prevalence of undernourishment(Khan, Hanjra, & Mu, 2009). On the other hand, the conversion of forest lands to cultivation land rise greenhouse gas concentration (DeFries et al., 2007) and causes climate change which lowers the amount of production(Montzka, Dlugokencky, & Butler, 2011).

An increase in the amount of yield produced has a positive effect on the application of agricultural inputs. The amount of crop production can be boosted also by increasing the productivity of land using the application of agricultural inputs like fertilizer and improved seed (Berhe, Gebretsadik, Edwards, & Araya, 2011). The application of improved seed can boost production by enhancing productivity and by reducing loss due to the incidence of pests and diseases. Chemical fertilizer has both direct and indirect effects on productivity. A higher application of chemical fertilizer means higher productivity (Bandyopadhyay, Misra, Ghosh, & Hati, 2010). But higher chemical fertilizer also lowers productivity, because it exacerbates land acidity (Golla, 2019)and climate change by increases greenhouse gas concentration, which is a main impediment factor to productivity (Xuejun & Fusuo, 2011).

The post-harvest loss also attributes to the prevalence of undernourishment by lower the amount of food supply. An increase in crop production contributes to GDP growth, this in turn increases the share of government expenditure on agricultural extension service. Expansion of extension service is a potential policy variable that can effectively reduce the amount of post-harvest loss, which means higher production and a low prevalence of undernourishment (Raidimi & Kabiti, 2017; Raidimi & Kabiti, 2019).

3.4 Causal Loop Diagram

To represent the feedback interaction between components of the system that causes the problem under study, Causal loop diagrams (CLD) are used. CLD is the easiest way to represent the feedback loop structure in the system. Several feedback loops connect the environment, social and economic aspects of crop production.

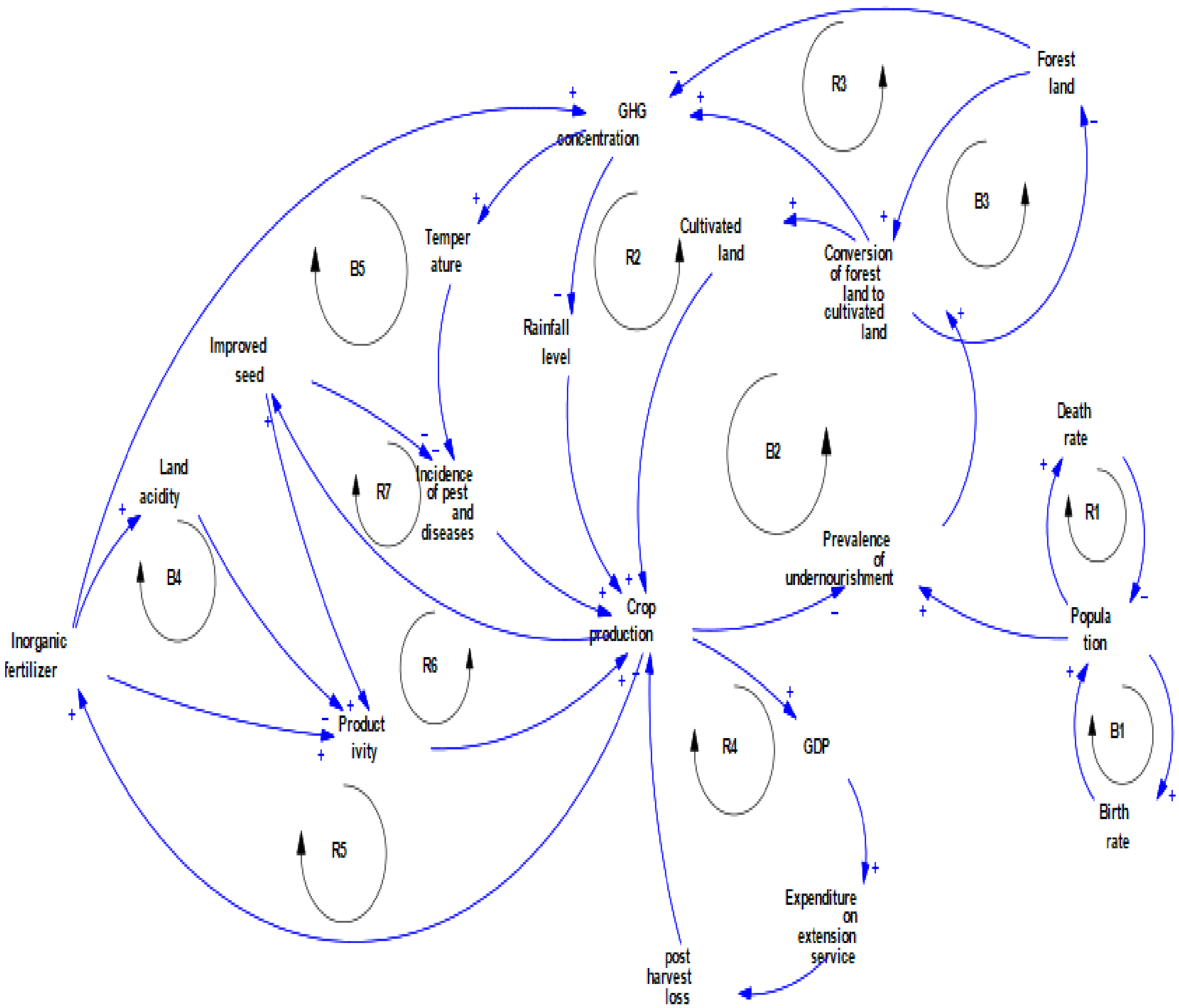


Figure 3.1: Causal Loop Diagram

We start by describing the feedback loop interaction that exists in the population sector. B1 is a balancing loop that shows the dynamics between population and death. When the number of the population raise, the number of death will raise, this in turn results decline in the amount of total population. While reinforcing loop R1 represents the relationship that exists between the number of birth and the total population. A high birth rate results in an increase in the population and more population led to high birth due to more population means there are more people ready to reproduce.

Now we proceed to examine the determinant of the prevalence of undernourishment. Growth in the population increases the proportion of the population that becomes undernourished. An increase in the prevalence of undernourishment forced the conversion of forest land to cultivation land. Expansion of cultivation land in turn increase the amount of crop produced, which means some proportion of undernourished people becomes nourished and the prevalence of undernourishment decline. This interaction is represented by Balancing loop B2.

While reinforcing loops R2 and R3 represent the interaction that exists among the prevalence of undernourishment, climate change, and production. The prevalence of undernourishment exacerbates the conversion of forest land to cultivation land, which means deforestation will aggravate. Deforestation will increase greenhouse gas concentration in the atmosphere and result in climate change. Temperature and rainfall levels are used as indicators of climate change (Espinosa, Portela, Matos, & Gharbia, 2022). Climate change hampered crop production (N. C. Turner et al., 2011) and result in more prevalence of undernourishment, this interaction is depicted by R3. On the other hand, besides emissions due to deforestation, the conversion of forest land to cultivation land shrinks the potential of forests to dispose of emissions from the atmosphere. This produces higher GHG concentration, climate change, lowers crop production, and higher undernourishment; this interaction is represented by reinforcing loop R3.

We use the post-harvest loss to explain reinforcing loop R4. Harvest and post-harvest loss reduce the amount of crop produced. A decline in crop production hampered GDP growth. This reduces government expenditure on agricultural extension services and causes higher post-harvest loss and a further decline in crop production.

Balancing loops B4, B5, and Reinforcing loop RS represent the interaction of inorganic fertilizer with productivity, land acidity, GHG concentration, and crop production. R5 shows an increase in crop production will enable the higher application of inorganic fertilizer and this increases productivity and production. While balancing loop B4 shows the application of inorganic fertilizer causes land acidity in the long run, this will reduce both productivity and production levels. The use of inorganic fertilizer is also responsible for GHG concentration that brings climate change and hampers crop production.

Improved seed is used to explain Reinforcing loops R6 and R7. Application of improved seed enhances productivity and boosts production level, which in turn results in more application of improved seed next year, represented by reinforcing loop R6. The improved seed is also an important technology to reduce loss due to pests and diseases. R7 demonstrate an increment in crop production due to the use of improved seed by reducing loss due to pest and diseases.

3.5 Stock and Flow Diagram

The stock-flow structure of crop production in Ethiopia is covered in this section. A stock and flow diagram combines stocks, flows, and auxiliary variables to construct a genuine system. It is a quantitative technique used to demonstrate the causal relationship between variables and to create an equation between them. Some variables build up over time and can never be negative; these are referred to as stocks. The size of the system's intake and outflow determine its stock. The factors that cause the stock to accumulate and deplete are called flows. Stocks lessen their outflow from their intake. Stock and flow variables are connected using an integral or differential equation. One way to differentiate stock variables from flow variables is by the unit of measurement. Flows are measured by unit per time, while the dimension of stock is expressed only by unit. To add extra information, to represent external parameters, or to intermediate steps between stock and flow, an Auxiliary variable is needed (Martinez- Moyano & Richardson, 2013; J. D. Sterman, 2002).The stock and flow diagram of our model has six stock variables. They are population, the prevalence of undernourishment, forest land, cultivated land, Greenhouse gas concentration, and livestock. Various differential and algebraic equations were used based on relevant literature to express the feedback link that connects stocks with flow variables (Homer & Hirsch, 2006). Stock and flow structure of the model together with, model equations, units, and variables value attached in appendix A.

Chapter 4 Model validation and behavior analysis

Building confidence to utilize the model for a certain purpose is the aim of model validation. Model validation is required to determine how well a simulation represents the real system for a certain research objective. As long as they can replicate the behavior of the real system, models are crucial tools. To validate a system dynamics model, both qualitative and quantitative techniques are applied. System dynamics places more emphasis on broad historical trends than on particular data points when validating models. The validity of the proposed model is examined using a variety of tests (Sweeney & Sterman, 2000).

Structural validation tests and behavioral validation tests are necessary to test in the system dynamics model (Yaman Barlas, 1989). The structural validation test is used to determine whether the model's structure adequately replicates the real structure of the system being studied. On the other hand, behavioral validation tests are used to contrast the behavior of the real system with that of the simulated model. Before doing a behavioral validity test, a structural validity test must be conducted because a model with structural errors might nonetheless replicate behaviors well. Once the model's structure has been verified, behavioral tests can be run to determine the model's overall validity. Any inaccurate pattern forecasting is the result of misinterpreting exogenous factors and parameters as long as the structure's quality is validated (Yaman Barlas, 1989).

4.1. Model structure validity tests

The extreme condition test, parameter verification test, structure verification test, dimensional consistency test, and boundary adequacy test are the five tests used to assess the model's structure (Forester & Senge, 1980; Sweeney & Sterman, 2000). These tests are categorized by Yaman Barlas (1996a) as direct structure tests and tests that are structure-oriented. The border adequacy test is categorized as a structure-oriented test, while the first four tests are considered to be direct structural tests.

4.1.1 Structure verification test

This test is important to check whether the model structure accurately depicts reality. The structure of the real system is compared with the structure of the model. According to Forester and Senge (1980), a model will pass a structure verification test if it is in line with the underlying knowledge about the real system. As Barlas (1996) suggested numerical data are the least important to undertake a structural verification test, it is qualitative. A casual loop diagram is used to compare the structure of the model with the structure of the real system (Bosch, Maani, & Smith, 2007). In this test, the structure of the causal loop diagram and the equation in the model will be compared with the structure and the relationship of variables in the real system respectively. It is important to efficiently grab the available knowledge about the issue under study and to consider existing models.

The casual loop diagram of the crop production sector in Ethiopia was discussed in section 3.3. The conceptual model of crop production was developed based on the review of relevant literature and government documents. Different system dynamics models that related to crop production were used as a guideline (Ayenew, 2013; Nasrin, 2020). After the structure of the model has been developed based on available knowledge and previous models, model verification by an expert who has sufficient knowledge on the subject is needed. To do this, the author's advisor was used to review the structure of the model and assumptions about the casual loop diagram and stock flow diagram. This step assures that the structure of the conceptual model is enough to represent the real system as well as the equations in the stock flow diagrams sufficiently replicate the causal interaction in the actual system. The model was developed based on available reliable evidence to demonstrate the interdependence of crop production and the environment and its impact on the prevalence of undernourishment.

4.1.2 Parameter verification test

It is useful to test the consistency of parameters with the existing numerical knowledge. Parameter verification of the model is done in the same way as structural verification against the structure of the real system (Forester & Senge, 1980). The value of auxiliary and exogenous variables must be consistent with theoretical and empirical knowledge of the real system.

All parameters that are employed in the model should have a counterpart in reality, and their value must be within the acceptable range. The value of parameters that were used in the SFD was sourced from existing empirical data and knowledge. The value used in parameterizing and initializing the model was taken from a reliable source. The initial value of stocks and parameters value is presented together with the equation of the model in appendix B.

4.1.3 Extreme conditions test

It is an important model validation test in system dynamics to check whether the model is credible in response to shocks extreme policies and extreme parameter values. The model should have to produce realistic results under extreme values. This test is important to discover any drawbacks in model structure and enable the identification of omitted variables (Forester & Senge, 1980). Extreme condition test validity is undertaken by subjecting parameters to extreme cases whose outcome on a real system is known definitely. Extreme condition tests can be done using the step function by introducing shock to the system (Bosch et al., 2007). In this section, we test extreme conditions for crop productivity and deforestation rate.

We undertake extreme condition tests for crop productivity. Crop productivity was assumed as an important determinant of crop production. To undertake extreme value analysis, we assess the condition that arises when crop productivity = 0. Under this extreme condition, the amount of crop produced is expected to become zero. Figure 4.1 below shows the simulation result,

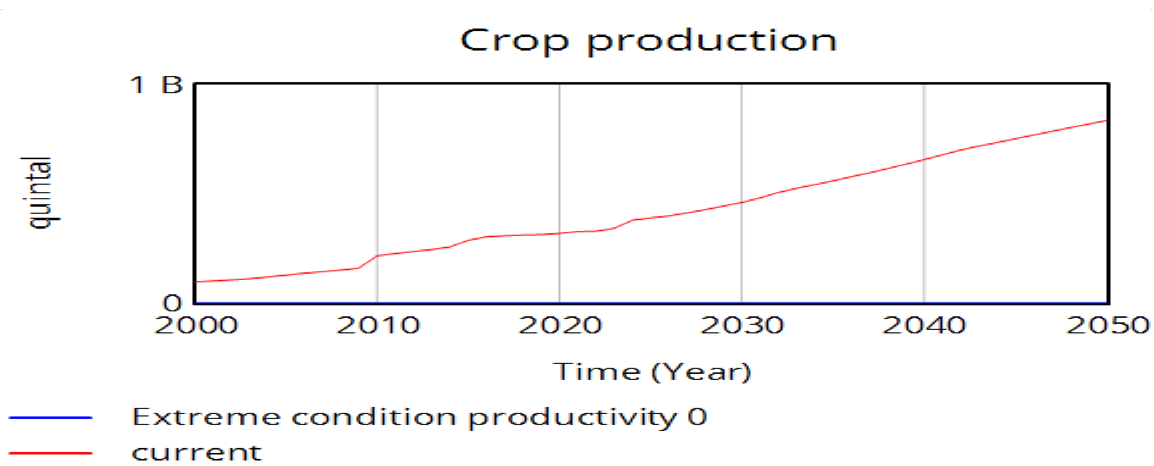


Figure 4.1: Simulation results for crop production under extreme tests of crop productivity

As shown in figure 2 under the extreme case of crop productivity (crop productivity = 0), the amount of crop production becomes zero (blue color). The amount of crop production is determined by the amount of cultivated land per hectare multiplied by land productivity in yield per hectare. When the productivity of land became zero, the amount of production also goes to zero.

Secondly, the deforestation rate is tested for extreme conditions. The deforestation rate is an auxiliary variable that determines the stock of forest land. An extreme condition test is made for the deforestation rate to investigate its impact on forest land, we take deforestation rate = 1(100%). Under this extreme condition, the amount of land covered by forest is expected to become zero because all forests are deforested.

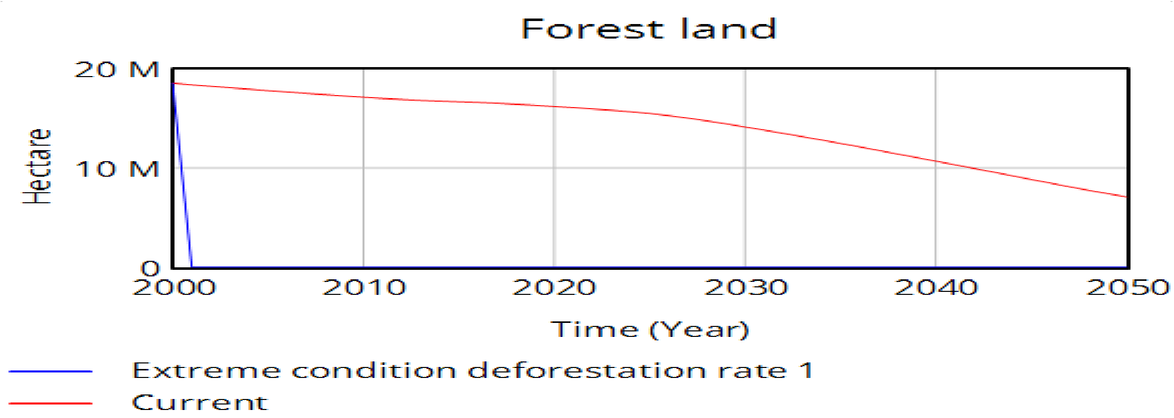


Figure 4.2: Extreme condition test for the conversion rate of forest land to cultivated land

The simulation result in Figure 4.2 shows that when the deforestation rate reaches 1 (100%), the forest land goes down to zero (blue color). this result is realistic and expected, it implies that all forest land is cleared due to deforestation.

4.1.4 Boundary Adequacy

This test is useful to evaluate whether or not significant variables are endogenous. It enables the evaluation of whether the conceptual model comprises all necessary variables and the appropriateness of the aggregation (Forester & Senge, 1980). The boundary of the model is expected to relate to the objective of the model for the model to be able to serve its intended purpose. The objective of the crop production sector model is to investigate the effect of different policy scenarios on the amount of crop produced, the prevalence of undernourishment, forest, and cultivated land, Greenhouse gas emissions, and loss due to post-harvest and pest and disease incidence. Always there is an intension to make more variables endogenous and expand the structure of the model. But this can be done only when the additional variable has a significant effect on the purpose of the study. The advice of the author’s supervisor was largely important in assure the adequacy of the boundary.

4.1.5 Dimensional consistency test

Most of the time dimensional consistency is tested together with a parameter verification test (Forester & Senge, 1980). The dimension of variables and parameters are needed to be similar to their counterpart in the existing knowledge. In the current model, the dimension of all variables is consistent with their counterpart in the real system. Dimensional analysis of constants, endogenous variables, stocks as well as inflows and out flow of the system were undertaken to verify dimensional consistency. This test was undertaken using Vensim modeling software. The software has a built-in function that checks for the dimensional consistency of each equation and variable and highlights equations where there is unit inconsistency. This software was used throughout the dynamic modeling process. Some variables with their unit are presented below in table 1.

Name of variable	Type of variable	Unit
Prevalence of undernourishment	Stock	Person
Forest land	Stock	Hectare
Cultivated land	Stock	Hectare
Conversation of cultivation land to non-fertile land	Flow	Hectare/year
Conversion of forest land to cultivated land	Flow	Hectare/year
Greenhouse Gas Concentration	Stock	Kg CO2
Population	Stock	Person
Livestock	Stock	TLU
Population growth	Flow	Person/Year
Population growth rate	Auxiliary	1/year
Net population growth rate	Auxiliary	1/Year
The conversion rate of forest land to cultivated land	Auxiliary	1/Year
Reforestation	Flow	Hectare/Year
Irrigation rate	Auxiliary	1/year
Share of Inorganic fertilizer	Auxiliary	Dmnl
Share of government expenditure on extension service	Auxiliary	Dmnl
Emission growth	Flow	Kg CO2/Year
Emission disposal	Flow	Kg CO2/Year

Table 1 Dimensional consistency test

4.2 Model behavior validity tests

After the structure of the model is validated using the above five model structure tests, it is possible to carry out a behavior validity test. It is used to investigate whether the model gives the expected trend over time. These tests are another way to test the accuracy of the model structure by measuring to what extent the model structure replicates the behavior of the real system over time. Behavior validity tests can be easily done quantitatively unlike most model structure tests which are highly qualitative (Yaman Barlas, 1996a).

The behavioral validation test is easily done by comparing simulated data with historical data. According to Barlas (1996), the goal of the behavioral validation test is on pattern behavior produced by the model, not about point prediction. Behavior reproduction and sensitivity test are recommended for validation of model behavior.

4.2.1 Behavior reproduction test

This test is used to compare the behavior of the simulated model with historical behavior. It is highly important to check whether the simulated outcome produced by a model accurately replicates the behavior of the system modeled. Behavioral reproduction tests made for crop production, the prevalence of undernourishment, forest land, cultivated land, GHG concentration, population, and total fertilizer use are presented below.

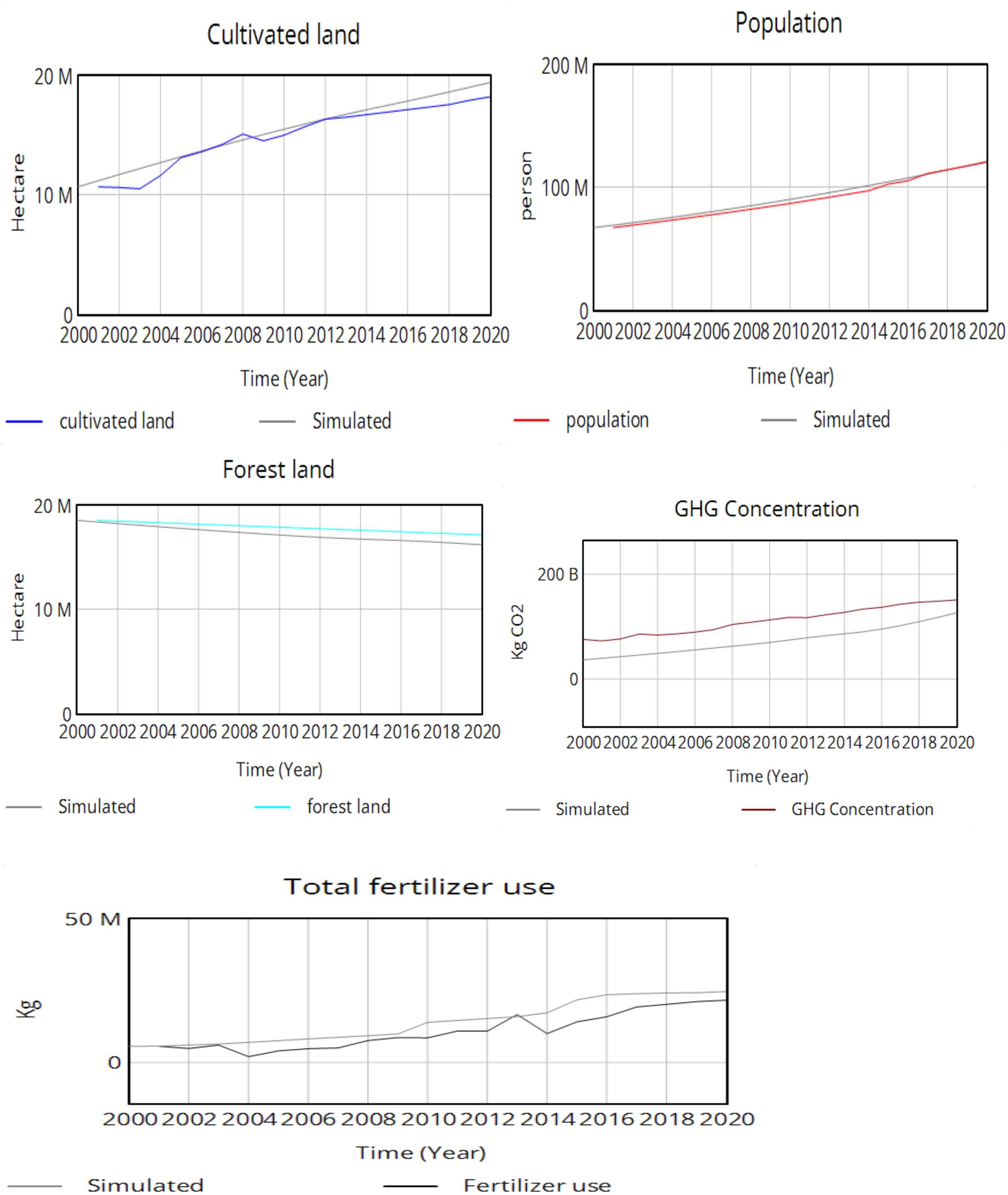


Figure 4.3: Behavioral reproduction test for selected variables

4.2.2 Behavior sensitivity test

It is used to investigate whether the model is sensitive to parameters. This test investigates how sensitive the model behavior is to changes in parameter values. The behavioral sensitivity test was not restricted to investigating the sensitivity of the model, rather it also examine the sensitivity of the real system to change in such parameters. The absence of high sensitivity builds trust in the model; however, the presence of such sensitive parameters does not invalidate the model (Forester & Senge, 1980). If the real system is also highly sensitive to these parameters, then these variables become valuable for policy experimentation.

We use a 50% confidence interval between the two simulations. The share of expenditure on extension services is the amount of budget allocated for the expansion of agricultural extension services. As discussed in the causal loop diagram extension service has causal interaction with crop production and the prevalence of undernourishment. An increase in the share of expenditure on extension services will lower the amount of postharvest loss, resulting in an increment in crop production and a decline in the prevalence of undernourishment. But a lower level of extension service results in a higher amount of post-harvest loss, and hence a low amount of crop yield and a rise in the prevalence of undernourishment. Figure 4.4 shows the sensitivity analysis of Postharvest loss, crop production, crop productivity, and prevalence of undernourishment with the change in share of expenditure on extension service.

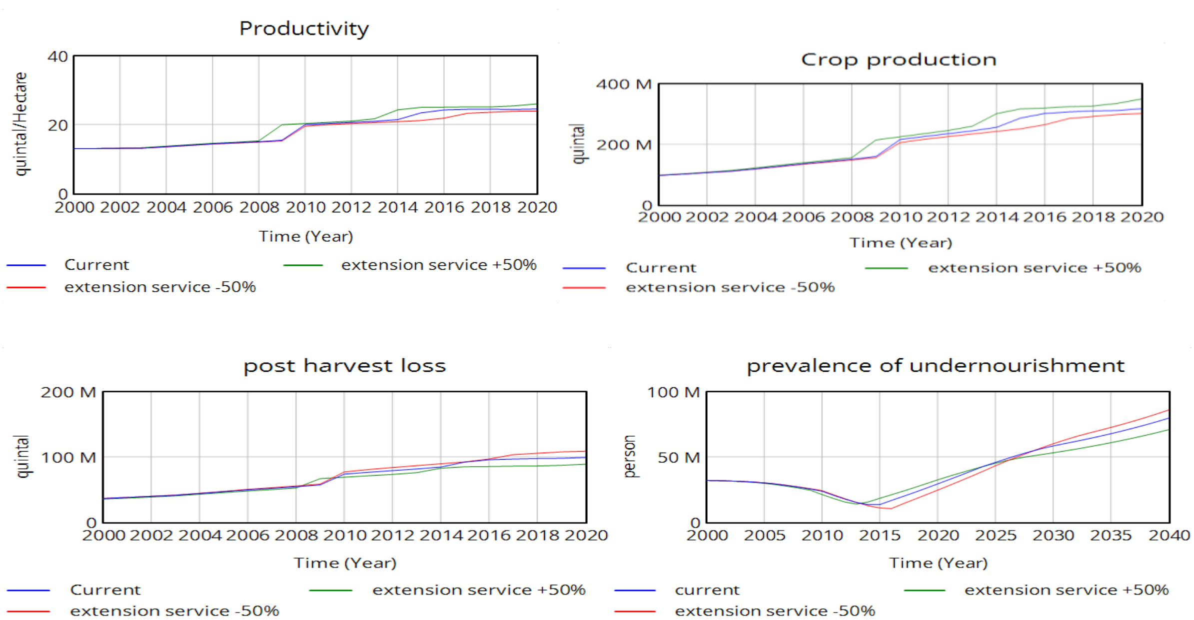


Figure 4.4: Sensitivity analysis for a share of expenditure on extension services

Now let us investigate the sensitivity of the model due to irrigation rate. The increase in irrigation rate will increase the amount of cultivated land and at the same time, it reduce deforestation because the demand for expansion of cultivation land is met by irrigation, which reduces the pressure on forest land. Since the expansion of irrigation reduces deforestation, it has a positive impact on forest land. Expansion of irrigation area also increases the amount of cultivated land. Subsequently, it causes an increase in crop production and a reduction in the prevalence of undernourishment. Figure 4.5 shows the sensitivity analysis of irrigation rate on deforestation, forest land, cultivated land, and crop production.

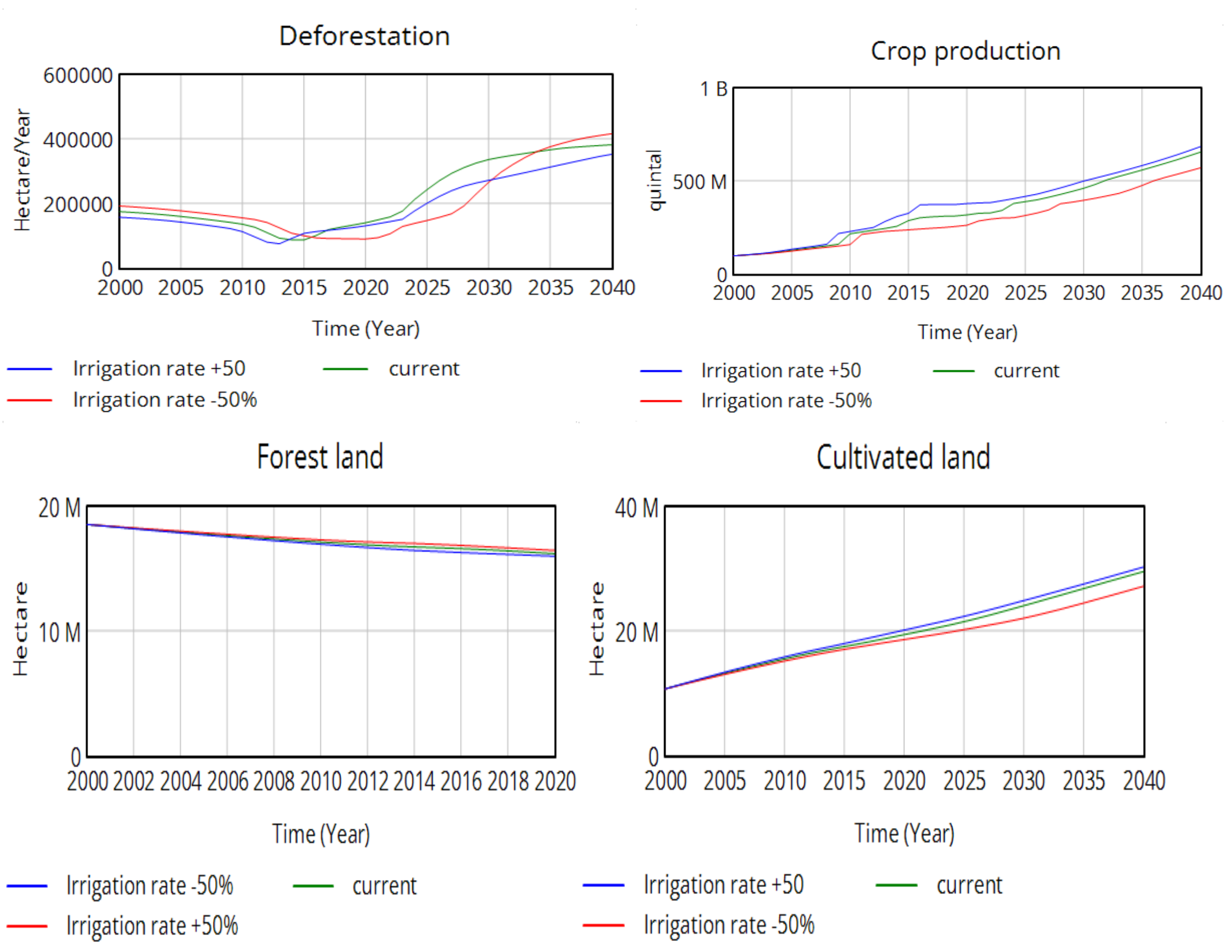


Figure 4.5: Sensitivity analysis for irrigation rate

Figure 4.5 shows that an increase in irrigation rate and lower deforestation level results in increases in forest land. On the other hand high irrigation rate increases the amount of cultivated land, hence level of crop production rise.

Let us examine the sensitivity analysis for the share of organic fertilizer. Organic fertilizer is a policy variable that has a positive environmental impact. An increase in the share of organic fertilizer will increase crop productivity and crop production as well as reduce the adverse impact of inorganic fertilizer on land acidity and GHG concentration. Here we will examine the sensitivity of crop production, crop productivity, GHG concentration, land acidity, forest, and cultivated land, and prevalence of undernourishment.

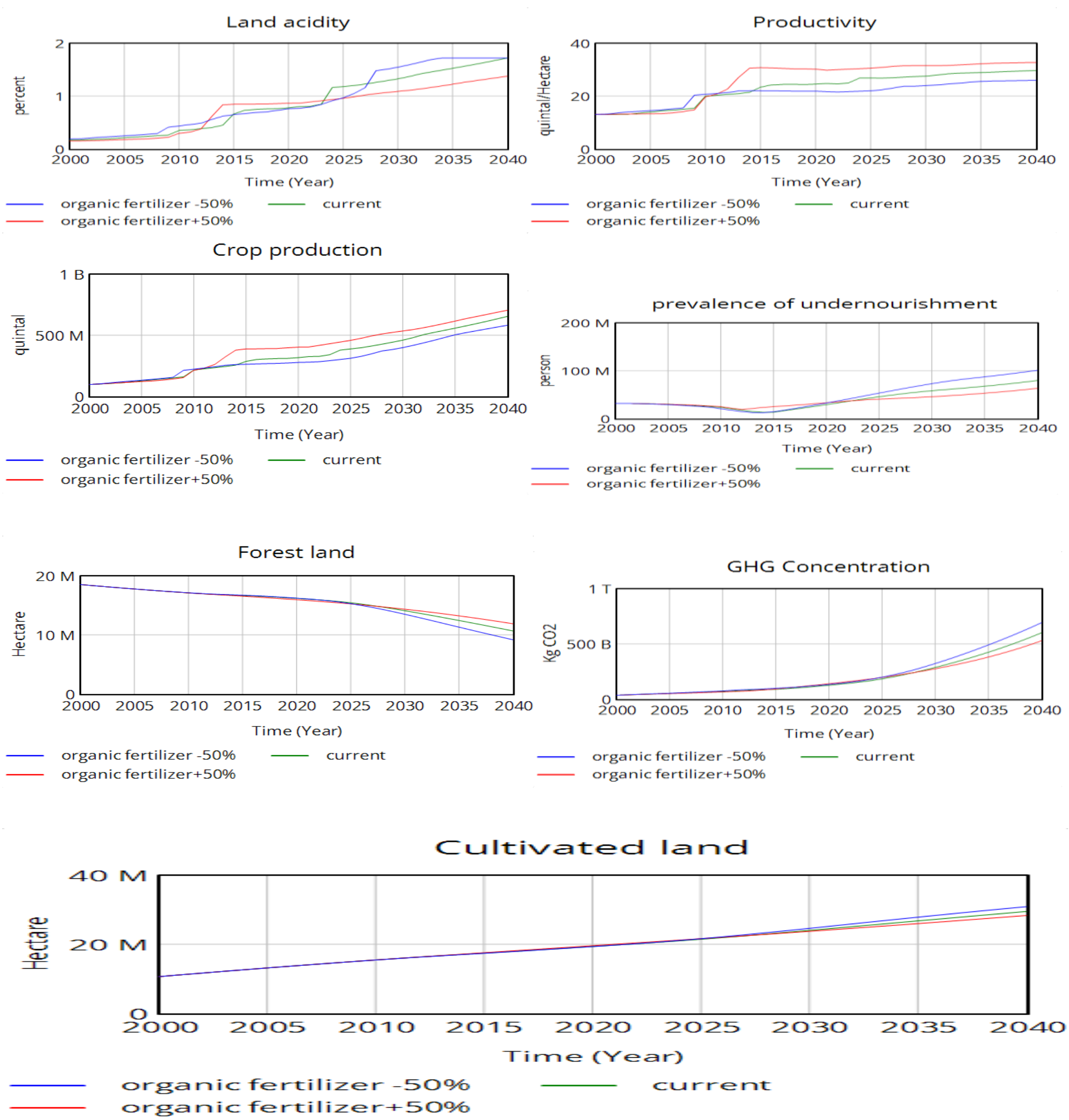


Figure 4.6: Sensitivity analysis for organic fertilizer.

The above figures show that the high application of organic fertilizer enhances productivity and crop production. Since organic fertilizer is capable of boosting production, the demand for expansion of cultivation land will slow down and result in an improvement in forest land and a reduction in GHG concentration. Additionally, higher use of organic fertilizer instead of inorganic fertilizer will minimize emissions from fertilizer and lower GHG concentration.

Forth, now let us examine sensitivity analysis foe improved seed. The application of improved seed increase crop productivity and reduce loss due to pest and diseases, thus leading to a higher amount of crop production. Hence it results in a decline in the presence of undernourishment.

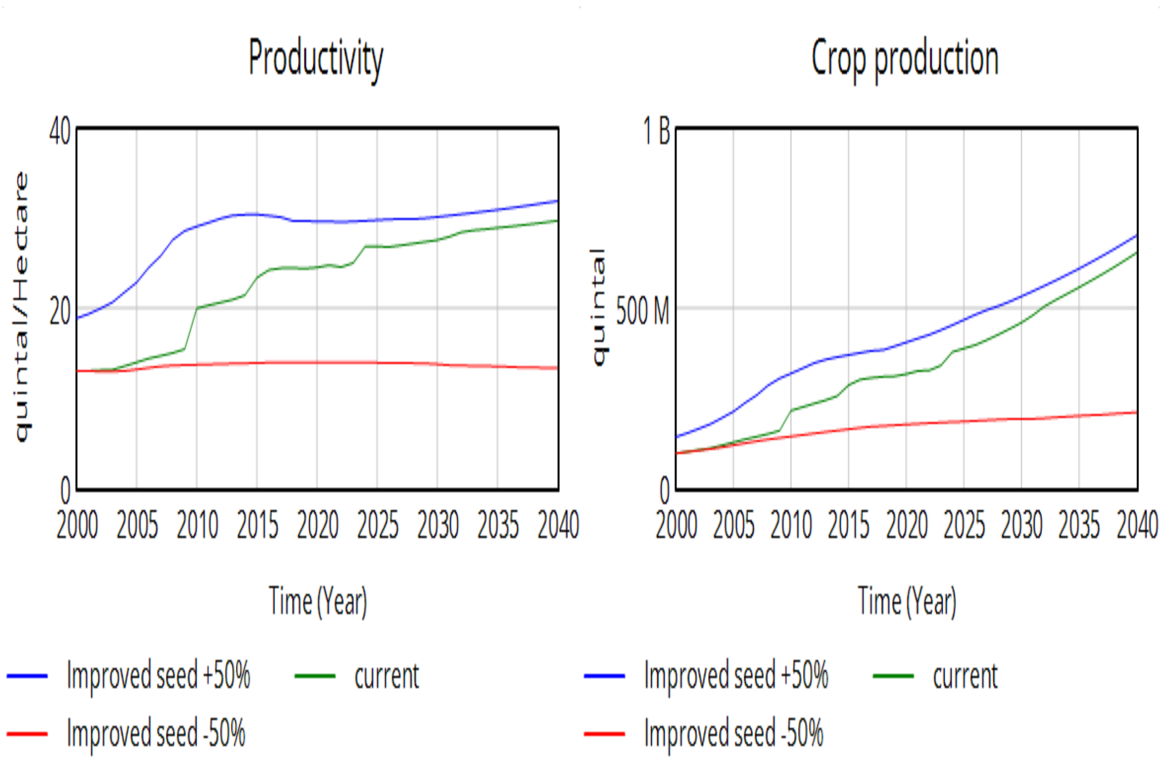


Figure 4.7: Sensitivity analysis for improved seed

As shown in figure 4.7, crop productivity and crop production are highly sensitive to changes in improved seed. This sensitivity is also expected in real systems.

4.3 Policy Analysis

The major importance of system dynamics is its easiness to conduct forecasting and policy analysis. In this section, we will discuss future potential policy alternatives and analyze scenarios for selected variables. Increasing crop production, environmental protection, and reducing the prevalence of undernourishment is the main target of policy analysis. The use of organic fertilizer, Increased improved seed, Expansion of extension service and Irrigation are the main policy alternatives.

4.3.1 Improved seed

Even if the trend for crop production in Ethiopia is increasing overtime, it has a lot more potential to increase the amount produced (Bati, 2020). The main factor which contributes to the inefficiency of crop production is related to poor application of improved seed. For instance, in the 2020/21 main season, the share of improved seed was less than 10% of the entire amount of seed (CSA, 2021). This policy focuses on increasing productivity through the intensification of agricultural input supplies, in this case, the application of improved seed. Improved seed is necessary to boost productivity and lower loss due to pests and diseases. As we discuss in the causal loop diagram, the application of improved seed gives a higher amount of yield through two channels. First, when the share of improved seed increases productivity (Maruod, Breima, Elkhidir, & El Naim, 2013). On the other hand application of improved seed reduce the incidence of pests and diseases, hence it reduces the loss associated with the incidence of pest and diseases. As GHG concentration rises, climate change will occur and this affects the temperature level. An increase in temperature level will create favorable conditions for the spread of pests and the occurrence of diseases. These pests and diseases result in huge losses in the amount of crop production. In Ethiopia, the loss due to pests and disease is estimated at around 40%, while the coverage of improved seed is around 10% in 2020/21. Since improved seeds have a great potential to resist pests and diseases, it is important to intensify the application of improved seeds to reduce loss and boost the amount of yield produced.

The main objective of increasing the share of improved seed is to reduce loss and increase productivity so that the amount of crop production will raise and the prevalence of undernourishment shrinks. We assume the share of improved seed to rise to 50% in scenario 1.

4.3.2 Expansion of agricultural extension services

The second policy option emphasizes the expansion of agricultural extension services to cult postharvest loss (McNamara & Tata, 2015). Expansion of agricultural extension service is important to reduce post-harvest loss, hence increasing the amount of crop production. The share of expenditure on agricultural extension services is less than 0.5%. So it is important to reduce the prevalence of undernourishment by increasing crop production. For a share of expenditure on agricultural extension service, we assume its share equals 0.5%.

4.3.3 Shift from Inorganic to organic fertilizer

This policy aimed at reducing the application of inorganic fertilizers for the health of the environment. The application of synthetic fertilizer harms the soil quality as well as contributes largely to GHG concentration. This implies that the application of organic fertilizer has the potential to preserve the soil quality (Cairo et al., 2017)and to cult GHG concentration from further increment. Moreover, the application of organic fertilizer is important to raise the level of productivity(Roba, 2018). Even if inorganic fertilizers are known for increasing land productivity, their adverse impact outweighs them in the long run. This is due to land acidity, the application of synthetic fertilizer results in land acidity which is the main reason for the low level of productivity. For Scenario 3 we assume the share of inorganic fertilizer is 25% and the share of organic fertilizer 75%.

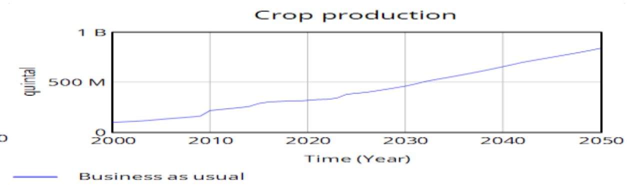
4.3.4 Expansion of Irrigation

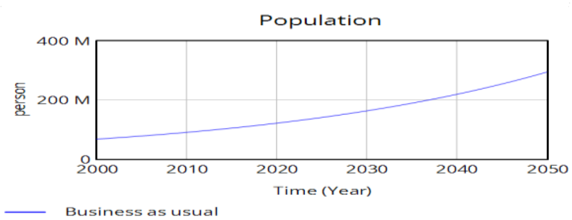
This is an important policy option to reduce GHG emissions that come from deforestation. Irrigation has great potential to boost crop production while reducing environmental impact specifically reducing deforestation. Expansion of irrigation will meet the demand for cultivation land and reduce pressure on forest lands for cultivation land. This results on the one hand an increase in cultivated land, hence higher production and lower prevalence of undernourishment. On the other hand, it reduces the amount of deforestation, which means deforestation emissions will lower the impact of climate change to some extent will be lowered. For scenario 4, the irrigation rate was assumed to increase to 20%.

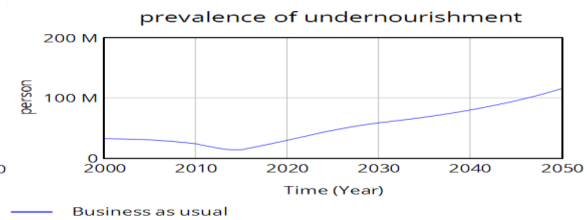
4.4 Base run

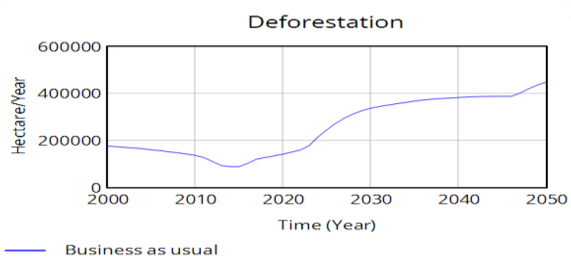
Our base run model simulated up to 2050. It is a simulation outcome before police scenarios are activated and exogenous variables continue the current trend. Figure 4.8 presents business as usual for some variables, Crop production, crop productivity, forest land, cultivated land, the prevalence of undernourishment, post-harvest loss, loss due to incidence and pest, GHG concentration, and deforestation.

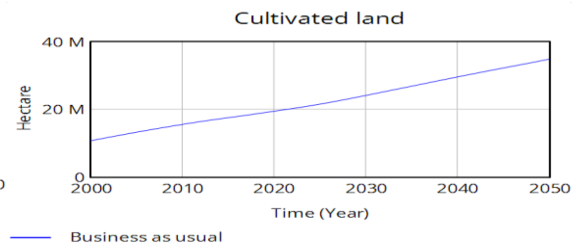

Productivity
quintal/Hectare
40
20
0
2000
2010
2020
2030
2040
2050
Time (Year)
Business as usual

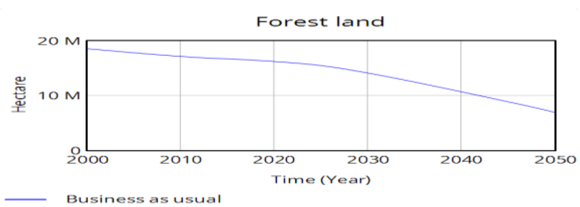

Crop production
quintal
1 B
500 M
0
2000
2010
2020
2030
2040
2050
Time (Year)
Business as usual

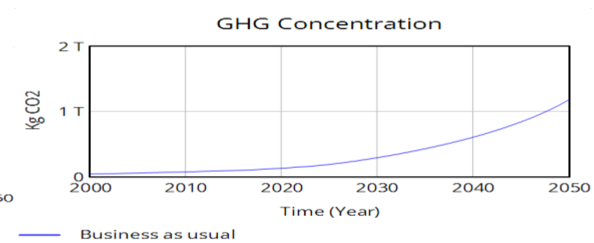

Population
person
400 M
200 M
0
2000
2010
2020
2030
2040
2050
Time (Year)
Business as usual

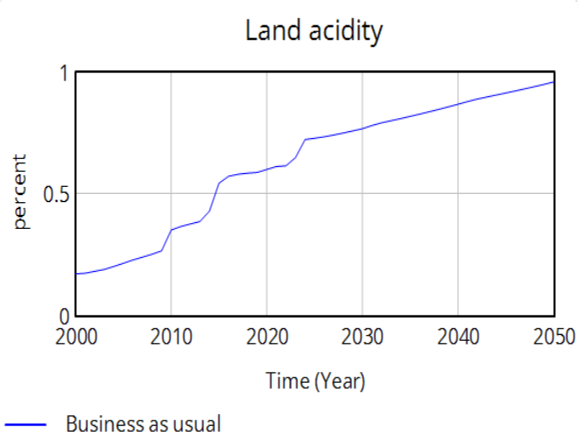

prevalence of undernourishment
person
200 M
100 M
0
2000
2010
2020
2030
2040
2050
Time (Year)
Business as usual

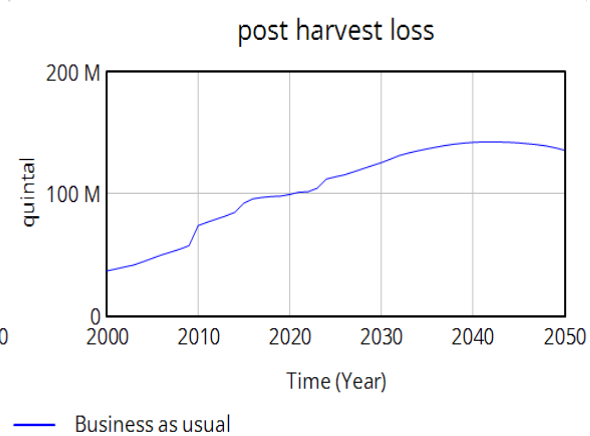

Deforestation
Hectare/Year
600000
400000
200000
0
2000
2010
2020
2030
2040
2050
Time (Year)
Business as usual


Cultivated land
Hectare
40 M
20 M
0
2000
2010
2020
2030
2040
2050
Time (Year)
Business as usual


Forest land
Hectare
20 M
10 M
0
2000
2010
2020
2030
2040
2050
Time (Year)
Business as usual


GHG Concentration
Kg CO2
2 T
1 T
0
2000
2010
2020
2030
2040
2050
Time (Year)
Business as usual


Land acidity
percent
1
0.5
0
2000
2010
2020
2030
2040
2050
Time (Year)
Business as usual


post harvest loss
quintal
200 M
100 M
0
2000
2010
2020
2030
2040
2050
Time (Year)
Business as usual

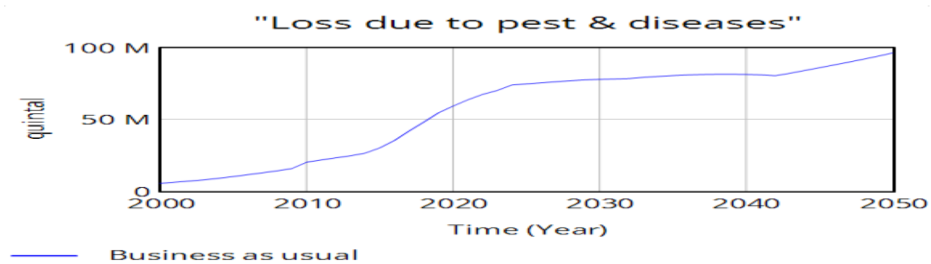


Figure 4.8: Base as usual run scenario for selected variables.

As shown in above figure 4.8, crop productivity and production continue to grow for 30 years 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. The sharp increase in the prevalence of undernourishment after 2020 exacerbates the deforestation rate and led to the conversion of forest land to cultivation land. Increasing use of inorganic fertilizers together with deforestation 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 pests and diseases. Inorganic fertilizer also causes an increasing trend of land acidity. The reduction in deforestation rate around 2014 is due to a decline in undernourishment. An increase in crop production cannot able to stop the prevalence of undernourishment from increasing. This shows that under the current production system, it is impossible to either achieve food security or environmental sustainability. The proportion of undernourished population estimated to increase from 24.9% in 2020 to 41% by 2050.

From base run scenario we can identify land acidity, post-harvest loss and loss due to pest and diseases as the major bottleneck of the sector. Due to unsustainable use of chemical inputs land acidity exacerbate which reduce soil quality and hamper land productivity, coupled with loss due to pest and diseases and post-harvest loss results low level of crop production relative to the demand of growing population. This increase undernourishment and causes deforestation for expansion of cultivation land.

4.4.1Policy of improved seed Implemented

This policy aimed at keeping the natural resource from depletion by reducing the conversion of forest land to cultivated land. So the goal is to avoid the expansion of cultivation land to increase production, by enhancing productivity of agricultural productivity. The policy is activated in 2025.

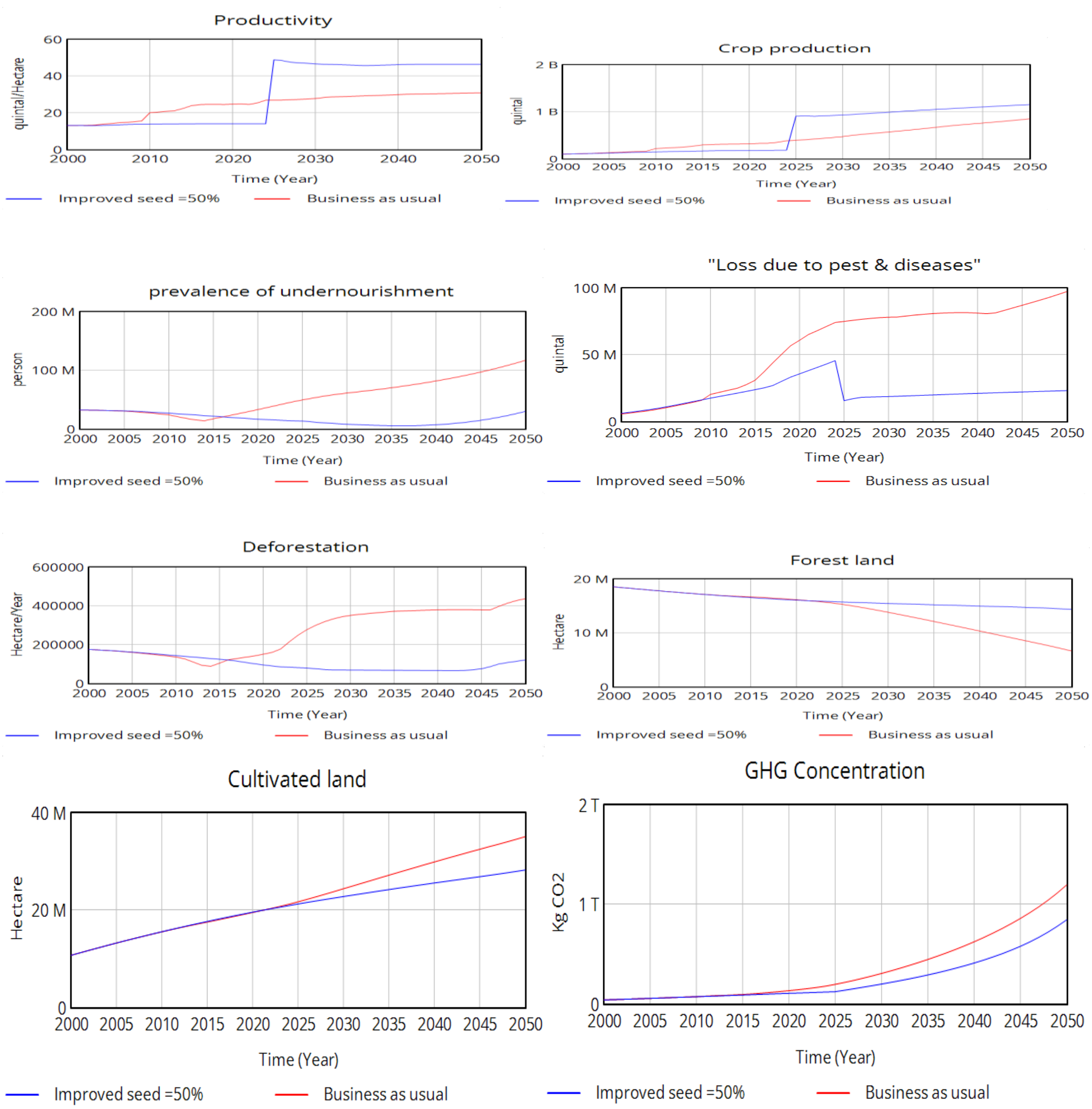


Figure 4.9: Comparison of Improved seed policy and BAU

The above graph shows that, when the share of improved seed rise to 50%, it increases productivity (Ojo, Saleh, Coker, & Ojo, 2019) and a reduction in loss due to pest and diseases, these two factors result in a dramatic increase in crop production. An increase in crop production in turn reduces the prevalence of undernourishment. Moreover, an increase in productivity due to the application of improved seed, reduce demand for cultivation land, and slowdown deforestation rate (Pelletier, Ngoma, Mason, & Barrett, 2020). Additionally, the improvement in crop production lowers the number of undernourished people, which reduces the pressure on forest land. As a result of low demand for cultivation land, deforestation is reduced and forest land conserved this results decline in GHG concentration in the atmosphere, this is due to the emission from deforestation is lowered and the forest land dispose more GHG concentrations.

4.4.2 Agricultural extension service policy activated

We assumed the policy to increase the share of expenditure on agricultural services to 0.5% starting in 2025.

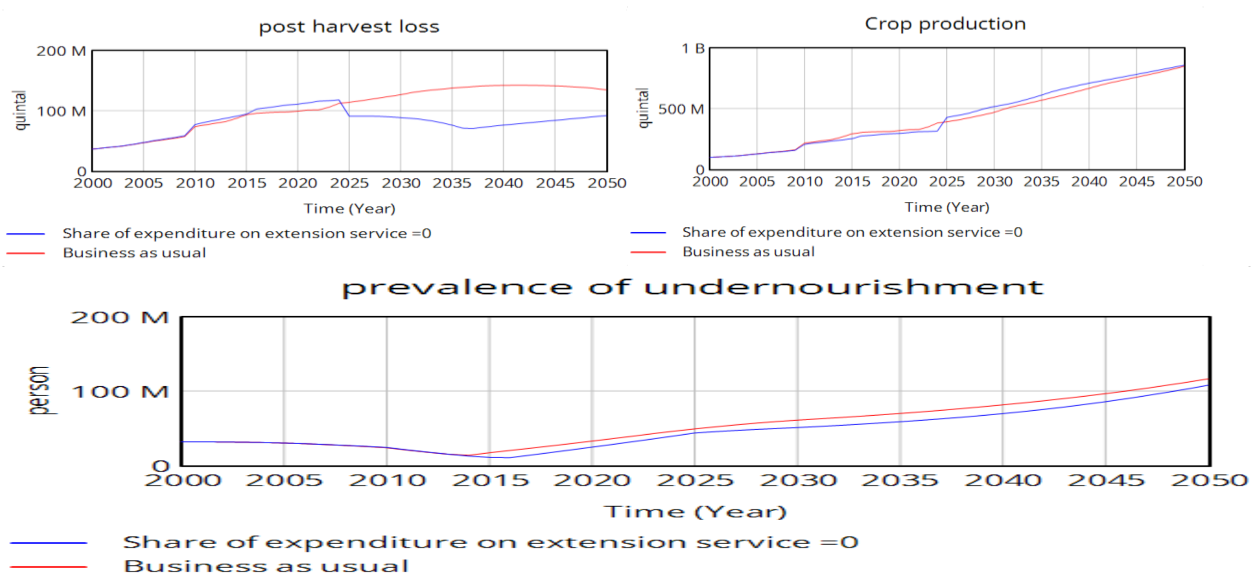


Figure 4.10: Comparison of agricultural extension service policy and BAU

The above graph shows that expansion of extension service results in a 50% reduction in post-harvest loss in 2040. Reduction in post-harvest loss in turn able to reduce the number of people undernourished(Majumder, Bala, Arshad, Haque, & Hossain, 2016).

4.4.3 Shift from inorganic to organic fertilizer policy implemented

As discussed early, the goal of this policy is to reduce the adverse impact of chemical fertilizer on soil quality and GHG concentration. Hence reduces the impact of soil acidity (Michael, 2021)and GHG concentration on crop production.

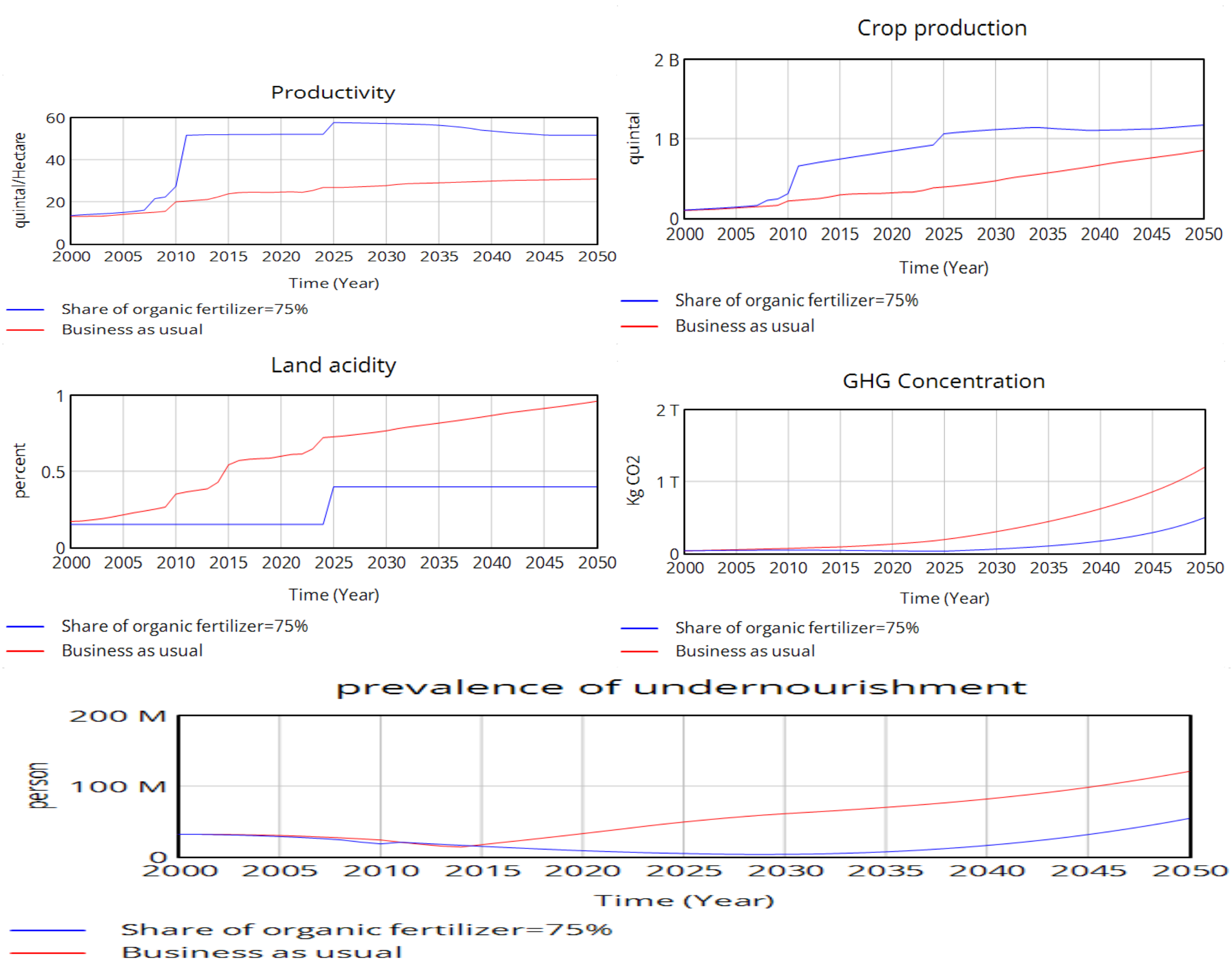


Figure 4.11: Comparison of Organic fertilizer policy and BAU

As shown in the above figure the application of organic fertilizer can enhance productivity. This is achieved through two-channel, an increase in organic fertilizer reduces land acidity that can be caused by inorganic fertilizer(Wang et al., 2019), and land acidity adversely affects productivity(Gemada, 2021), so the application of organic fertilizer can enhance productivity by lower the adverse impact of acidity, besides its direct positive effect. The application of organic fertilizer was able to reduce GHG concentration by reducing the share of fertilizer emissions (Liu et al., 2015). These effects results produce higher yield and lower the state of food insecurity.

4.4.4 Irrigation policy implemented

Irrigation policy aims to reduce the conversion of forest land to cultivation land, by irrigating semi-arid areas. We will expect a reduction in deforestation and GHG concentration as well as an increment in crop production, forest, and cultivated land.

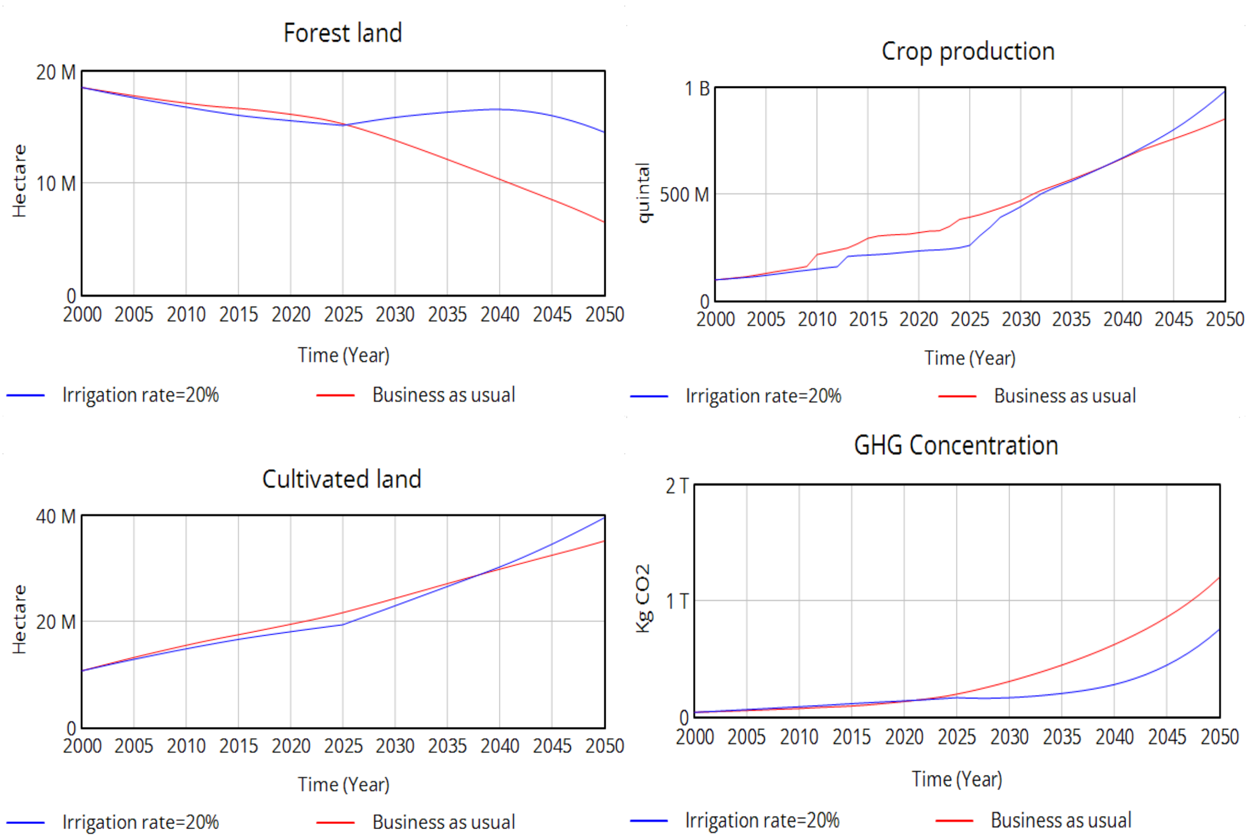
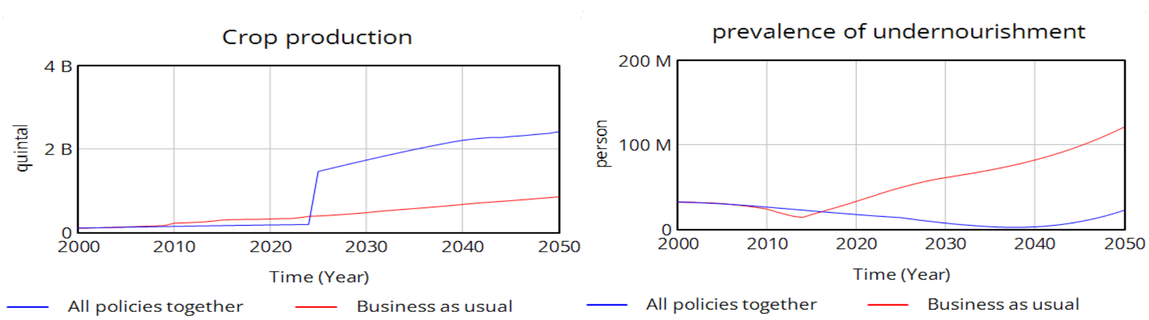


Figure 4.12: Comparison of Irrigation policy and BAU

The above graph shows that the expansion of irrigation area is capable of increasing cultivation area while reducing deforestation. It causes crop production to increase and thereby prevalence of undernourishment is reduced. Expansion of irrigation area also increases the forest land by lowering deforestation (Shively & Martinez, 2001); this enhances the emission disposal potential of forest and results in GHG concentration reduction.

4.4.5 All five policies together



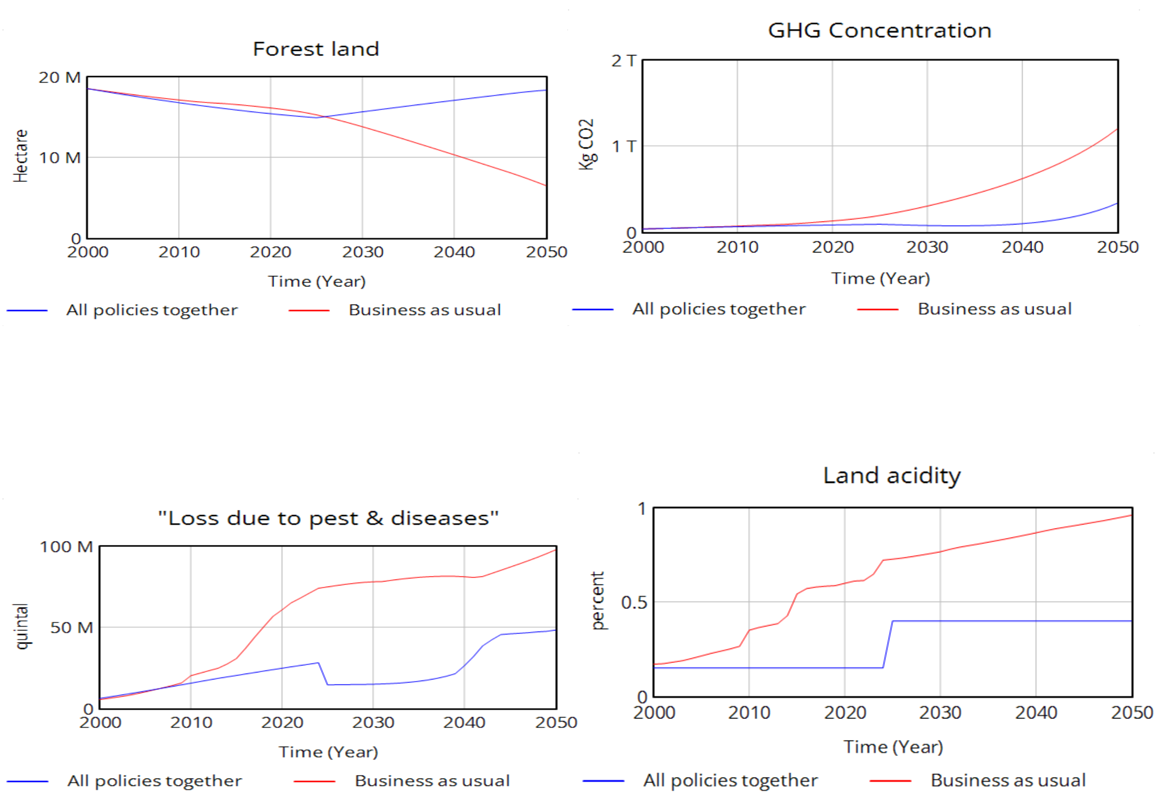


Figure 4.13: Effect of implementing all policies together for selected variables

The above figure shows, what can happen if all policy options are implemented together. As we have seen from the graphs, productivity, and crop production dramatically increased; this lowered the prevalence of undernourishment to less than 2 million in 2038. And it became possible to keep Land acidity, GHG concentration, forest land, and cultivated land at their level in 2025.

4.4.6 Comparison of effective policy for the selected variable

In this section, we will discuss which policy is efficient for selected variables.

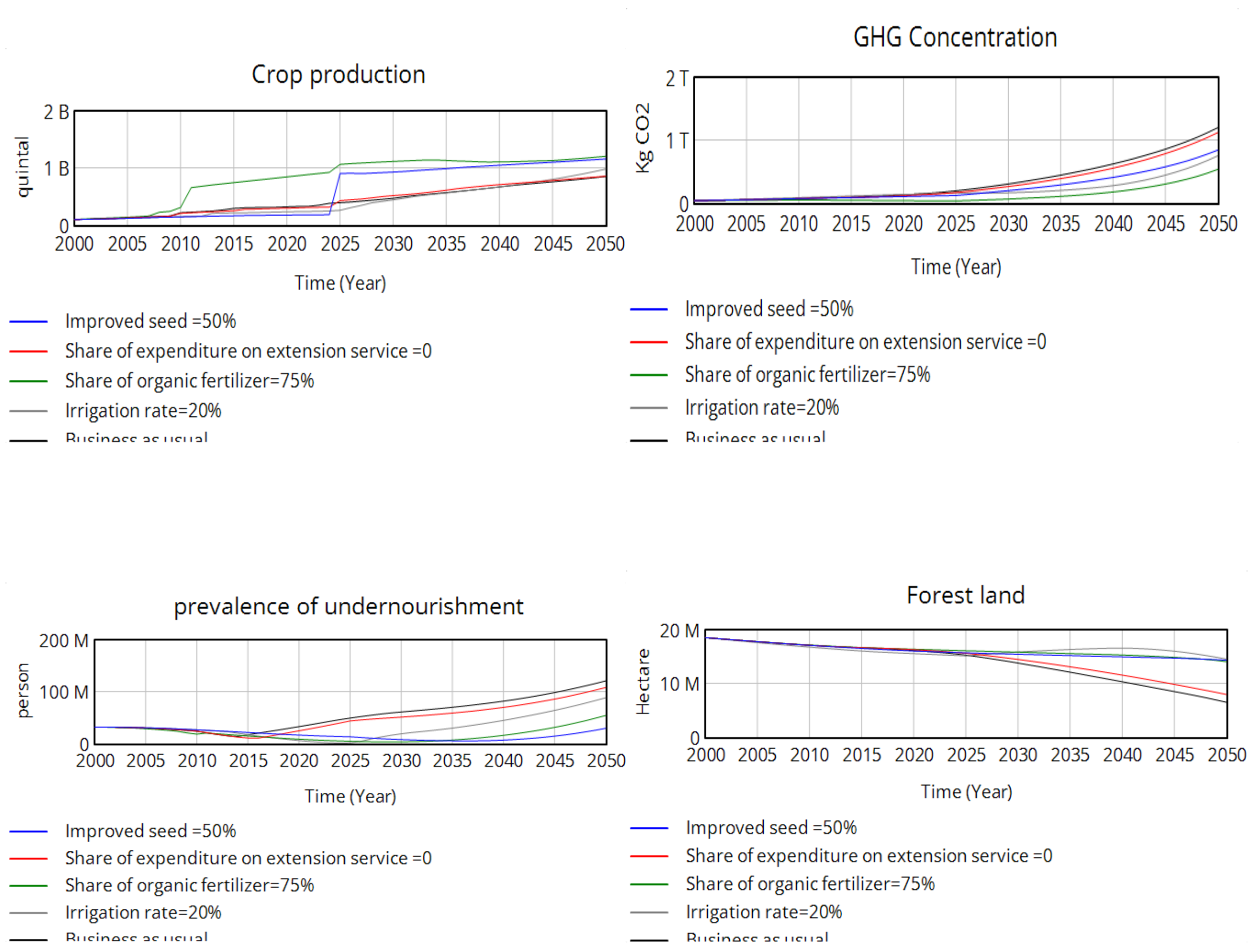


Figure 4.14: Response of some variables for policy changes.

As the figure demonstrates, the application of improved seed and organic fertilizer is found highly effective in boosting crop production and alleviating the prevalence of undernourishment. While irrigation rate followed by the application of improved seed and organic fertilizer found a potential policy option to preserve forest land. Application of organic fertilizer is significant in the reduction of GHG concentration followed by irrigation rate. This is because the application of organic fertilizer can reduce the emissions from chemical fertilizer which is an important source of emissions growth, while irrigation rate reduces GHG concentration by lower emissions that come from deforestation and enhancing the capacity of forest land to dispose of emissions.

Chapter Five: Conclusion

5.1 Major Findings

This study aimed to understand sustainability-related problems of crop production in Ethiopia. The amount of crop production has shown a positive trend in Ethiopia for decades. However, this improvement in crop production is below the country's potential and it was not able to alleviate the problem of food insecurity. Moreover, this progress is achieved at a severe cost to the environment, which poses a danger to the future level of production. All these factors indicate that the current production system is unsustainable.

The study of sustainability of crop production requires examining the interaction of (1) the growing food insecurity due to the growing population (2) the amount of crop produced which is dependent on the application of agricultural input and cultivation land (3) the environment, which affects the status of production. These components have a complex relationship that involves non-linearity, flow, stock, and feedback cycle that affect our understanding of the overall structure. For example, the effect of irrigation rate on GHG concentration, forest, and cultivated land, and crop production, and the effect of chemical fertilizer on GHG concentration, land acidity, productivity, production, and prevalence of undernourishment, etc. are some of the complex interactions found in studying the sustainability of crop production. To uncover the complex dynamic that exists among different variables, system dynamics modeling was used. It was also used to formulate potential policy options to mitigate the problem.

The base run scenario of the crop production model shows that post-harvest loss and loss due to pest and diseases coupled with land acidity led to unsatisfactory performance of crop production and severe food insecurity, exacerbating deforestation and GHG concentration, and so on, thus creating a vicious cycle. Therefore, the model recommended several policies for implementation: increasing the rate of irrigation to slow down the deforestation rate, shifting from inorganic to organic fertilizer to reduce land acidity and GHG concentration, reducing post-harvest loss through expansion of agricultural extension services, and increasing application of improved seed to raise productivity and cult incidence of pest and diseases.

The model was validated by using various model validation tests to assure its robustness and feasibility, it was proved that the model is realistic and capable of doing policy experimentation. Implementing all policies led to an increase in productivity and crop production, a reduction in deforestation, land acidity, and GHG concentration, and assures food security. Besides, the increased application of improved seed and organic fertilizer is a highly sensitive, effective, and feasible policy option that increases the amount of yield and reduces an environmental hazard. The policy of irrigation rate was successful in keeping the current level of forest cover from further deforestation. Lastly, from the simulation result, it is clear that the implementation of all policies will provide food sufficiency and environmental conservation in the future.

5.2 Limitation of the Study and Future Research Area.

The study tried to build a holistic model that reflects a real system as much as possible, but no model is perfect. The model has some limitations.

First, the boundary of the study includes rainfall variation and Temperature level as indicators of climate change. They were assumed to be affected by GHG concentration and in turn, they affect productivity and incidence of pests and diseases respectively. A more inclusive way of studying the effect of GHG concentration on crop production would be to include all effects of climate change such as flood, and drought.

Second, the study was aggregated at the national level. Since the study is at a national level, it needs great care to down-scale the interpretation of the outcome to regional and zonal levels. It may not give meaningful results in all regions. For instance, the prevalence of undernourishment and forest cover is not similar in the northern and southern parts of Ethiopia. There may be a significant difference between the northern and southern parts of Ethiopia regarding their potential for emission disposal and land productivity.

Third, we used aggregated amounts of crop production as a major determinant of the prevalence of undernourishment. This version of the structure was sufficient for this thesis. However, there is room to improve the model by disaggregating crop production either into wheat, maize, Teff, and so on or to cereal, vegetable, and fruit. Finally, the limitation of the study can be used as a future research area. It is possible to disaggregate into the regional level of Ethiopia. This enables one to understand a problem in detail and to provide efficient policies which are subjective to the situation of a specific region. There is also room to disaggregate crop production by type of crop production. Future work focusing on estimating the opportunity cost of each policy option are highly appreciable since it enables policymakers to compare the economic, social, and environmental impact of different policy options.

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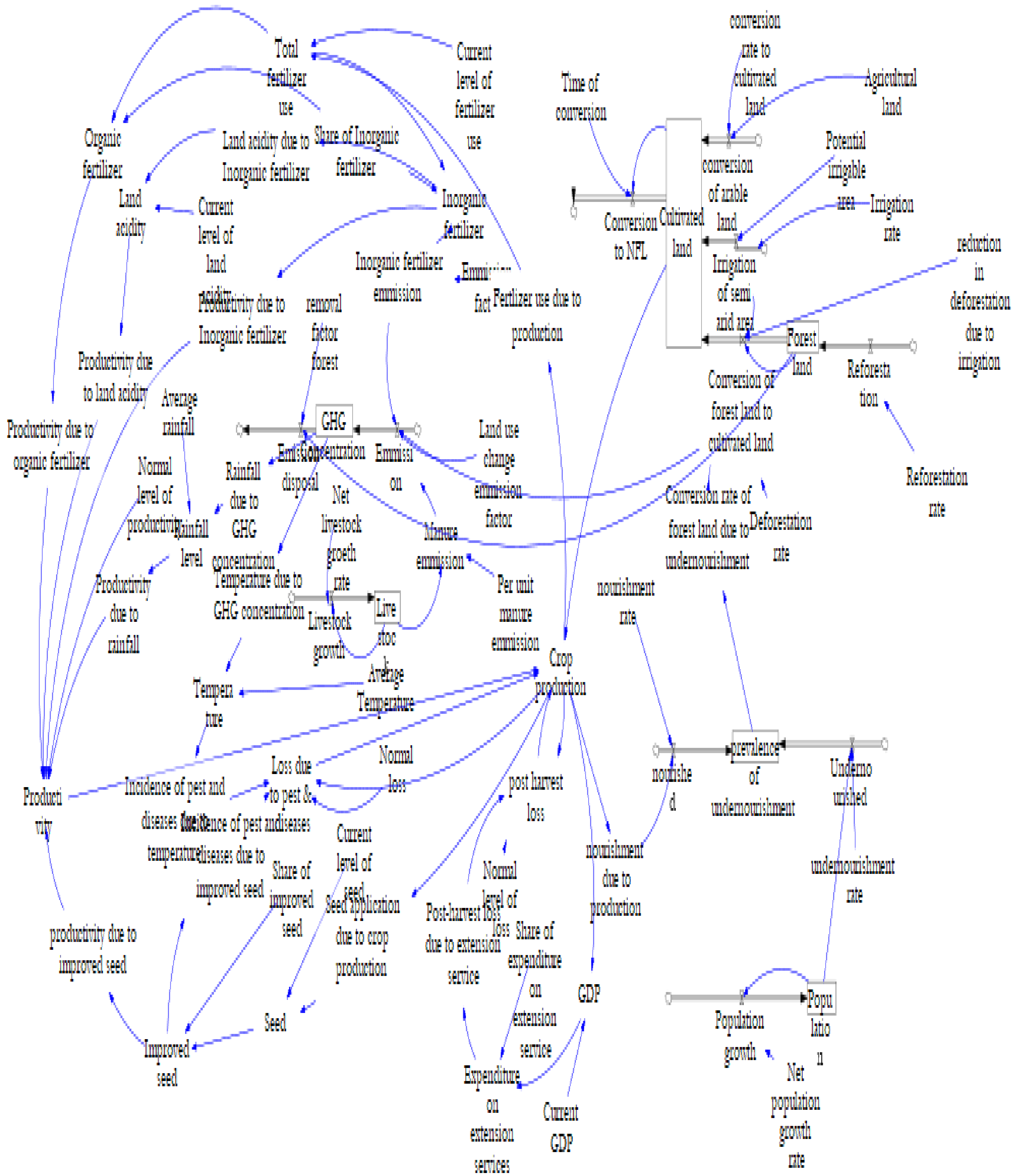
Appendix A: Stock and flow diagram



Appendix B: Model Equation

Agricultural land= 3.84761e+07

Units: Hectare

Average Temperature=25 Units: C

Conversion of arable land= conversion rate to cultivated land*Agricultural land

Units: Hectare/Year

Conversion of forest land to cultivated land=Conversion rate of forest land due to undernourishment*Deforestation rate*Forest land-Irrigation of semi-arid area/reduction in deforestation due to irrigation

Units: Hectare/Year

Conversion rate of forest land due to undernourishment= WITH LOOKUP (prevalence of undernourishment, ([(0,0)-(10,10)],(1e+07,0.8),(1.5e+07,0.9),(2e+07,1.12),(3e+07,1.3),

(3.84211e+07,1.5),(5e+07,2.5),(7e+07,4),(1e+08,6),(1.2e+08,9)))

Units: 1

Conversion to NFL= Cultivated land/Time of conversion

Units: Hectare/Year

Crop production= SIMULTANEOUS ((Cultivated land*Productivity)-post harvest loss-"Loss due to pest & diseases", 1e+08)

Units: quintal

Cultivated land= INTEG (conversion of arable land+ Conversion of forest land to cultivated land+ Irrigation of semi-arid area- Conversion to NFL,1.0662e+07)

Units: Hectare

Current level of fertilizer use= 5.09284e+06

Units: Kg

Current level of land acidity=0.43

Units: percent

Current level of seed= 4e+06

Units: quintal

Deforestation rate= 0.0084

Units: 1/Year

Emission disposal=Forest land*removal factor forest

Units: Kg CO2/Year

Emmission= Inorganic fertilizer emmission+ Manure emmission+ Land use change emmission factor*Conversion of forest land to cultivated land

Units: Kg CO2/Year

Emmission factor=400

Units: Kg CO2/Kg/Year

Expenditure on extension services= GDP*Share of expenditure on extension service

Units: birr

Fertilizer use due to production= WITH LOOKUP (Crop production,([(0,0)-(10,10)],(1e+08,1.09284),(2e+08,2.5263),(2.5e+08,3.2),(2.75e+08,4),(3e+08,4.6),(3.5e+08,5.3),(3.7e+08,6.1),(1e+09,10)))

Units: 1

Forest land= INTEG (Reforestation-Conversion of forest land to cultivated land, 1.85285e+07)

Units: Hectare

GDP=SIMULTANEOUS (Crop production*Current GDP, 6.3973e+10)

Units: birr

GHG Concentration= INTEG (Emmission-Emission disposal, 3.66331e+10)

Units: Kg CO2

Improved seed= Share of improved seed*Seed

Units: quintal

Incidence of pest and diseases due to improved seed= WITH LOOKUP (Improved seed, ([(0,0)-(10,10)],(147712,1.53788),(487032,1.34848),(672115,1.27273),(91889,1.09848),(1.30669e+06, 1.02273),(2.86227e+06,0.44697),(1.2e+07,0.1)))

Units: 1

Incidence of pest and diseases due to temperature= WITH LOOKUP (Temperature,([(0,0)-(10,10)],(24.12,0.1),(24.5,0.2),(25.24,0.25),(26,0.43),(26.69,0.5)))

Units: 1

Inorganic fertilizer=SIMULTANEOUS (Total fertilizer use*Share of Inorganic fertilizer,Total fertilizer use*0.75)

Units: Kg

Inorganic fertilizer emmission= Inorganic fertilizer*Emmission factor

Units: Kg CO2/Year

Irrigation of semi-arid area= Irrigation rate*Potential irrigable area

Units: Hectare/Year

Irrigation rate= 0.1

Units: 1/Year

Land acidity= Current level of land acidity*Land acidity due to Inorganic fertilizer

Units: percent

Land acidity due to Inorganic fertilizer= WITH LOOKUP (Inorganic fertilizer, ([(0,0)-(10,10)],(3.5e+06,0.35),(7.2e+06,0.6),(1.1e+07,0.85),(1.44e+07,1),(1.6e+07,1.17),(2e+07,1.29),(3e+07,1.4),(4e+07,2)))

Units: 1

Land use change emmission factor= 45300

Units: Kg CO2/Hectare

Livestock= INTEG (Livestock growth, 2.06846e+07)

Units: TLU

Livestock growth= Livestock*Net livestock growth rate

Units: TLU/Year

"Loss due to pest & diseases"=Normal loss*Incidence of pest and diseases due to temperature*Incidence of pest and diseases due to improved seed*Crop production

Units: quintal

Manure emmission=Livestock*Per unit manure emmission

Units: Kg CO2/Year

Net livestock growth rate=0.134

Units: 1/Year

Net population growth rate=0.03

Units: 1/Year

Normal level of loss= 0.25

Units: 1

Normal level of productivity= 12.66

Units: quintal/Hectare

Normal loss=0.4

Units: 1

Nourished= nourishment due to production*nourishment rate

Units: person/Year

Nourishment due to production= WITH LOOKUP (Crop production,([(0,0)-(10,10)],(9.5e+07,8.84e+06),(1.34798e+08,1.38636e+07),(1.68911e+08,1.75e+07),(2.0871e+08,2.22727e+07),(2.37137e+08,2.06818e+07),(2.56089e+08,1.29545e+07),(2.63669e+08,2.04545e+06),(3.81169e+08,8.18182e+06),(4.62661e+08,1.54545e+07),(5.85847e+08,1.6e+07),(7e+08,1.73e+07),(8e+08,1.85e+07),(1e+09,2e+07),(2e+09,2.6e+07)))

Units: 1

Nourishment rate=0.31

Units: person/Year

Organic fertilizer=Total fertilizer use*(1-Share of Inorganic fertilizer)

Units: Kg

Population= INTEG (Population growth,6.7e+07)

Units: person

Population growth=Net population growth rate*Population

Units: person/Year

Post-harvest loss="Post-harvest loss due to extension service"*Normal level of loss*Crop production

Units: quintal

"Post-harvest loss due to extension service" = WITH LOOKUP (Expenditure on extension services,([(0,0)(10,10)],(1e+08,1.5),(3e+08,1.26705),(6e+08,0.926),(8e+08,0.6875),(1e+09,0.4))

Units: 1

Potential irrigable area= 3.5e+06

Units: Hectare

Prevalence of undernourishment= INTEG (Undernourished-nourished,3.2e+07)

Units: person

Productivity=Normal level of productivity*Productivity due to organic fertilizer*Productivity due to land acidity*productivity due to improved seed*Productivity due to Inorganic fertilizer*Productivity due to rainfall

Units: quintal/Hectare

Productivity due to improved seed= WITH LOOKUP (Improved seed,([(0,0)-(10,10)],(400000,0.9),(500000,0.94),(600000,0.999),(700000,1.156),(800000,1.2253),(1e+06,1.),(1.2e+06,1.4),(1.4e+06,1.52),(2e+06,1.66),(4e+06,1.82),(6e+06,2.1),(1e+07,2.5)))

Units: 1

Productivity due to Inorganic fertilizer = WITH LOOKUP (Inorganic fertilizer, ([(0,0)-(10,10)],(4.8e+06,1),(6e+06,1.06),(9.6e+06,1.14),(1.48e+07,1.256)))

Units: 1

Productivity due to land acidity = WITH LOOKUP (Land acidity, ([(0,0)-(10,10)],(0.15,1.06),(0.2,1.053),(0.3,1.04),(0.4,1.025),(0.5,1.01),(0.6,1.0075),(0.7,1.004)))

Units: 1

Productivity due to organic fertilizer= WITH LOOKUP (Organic fertilizer, ([(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

Productivity due to rainfall= WITH LOOKUP (Rainfall level,([(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

Rainfall due to GHG concentration = WITH LOOKUP (GHG Concentration, ([(0,0)-(10,10)],(2e+10,1.12),(5e+10,1),(1e+11,0.8),(1.5e+11,0.5),(2e+11,0.4),(3e+11,0.33)))

Units: 1

Rainfall level=Average rainfall*Rainfall due to GHG concentration

Units: mm

Reduction in deforestation due to irrigation= 3

Units: 1

Reforestation= Reforestation rate

Units: Hectare/Year

Reforestation rate=19000

Units: Hectare/Year

Removal factor forest=355.5

Units: Kg CO2/(Year*Hectare)

Seed=Current level of seed*Seed application due to crop production

Units: quintal

Seed application due to crop production= WITH LOOKUP (Crop production,([(0,0)-(10,10)],(1e+08,1),(1.5e+08,1.4),(2e+08,1.9),(3e+08,2.8),(4e+08,3.8),(5e+08,4.9),(7e+08,6.3)))

Units: 1

Share of expenditure on extension service=0.0032

Units: 1

Share of improved seed=0.1

Units: 1

Share of Inorganic fertilizer= 0.75

Units: 1

Temperature=Average Temperature*Temperature due to GHG concentration

Units: C

Temperature due to GHG concentration= WITH LOOKUP (GHG Concentration, ([(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: 1

Time of conversion=100

Units: Year

Total fertilizer use=SIMULTANEOUS (Current level of fertilizer use*Fertilizer use due to production, 5.09284e+06)

Units: Kg

Undernourished=Population*undernourishment rate

Units: person/Year

Undernourishment rate= 0.04 Units: 1/Year