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ETHIOPIA
A Country Study on the Economic Impacts of Climate Change

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FIGURES

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CURRENCY EQUIVALENTS

(Birr)
Birr = 0.0997 $US
1 $US = 10.0 Birr

SYSTEM OF MEASUREMENT

Metric System

ABBREVIATIONS AND ACRONYMS

ADLI	Agriculture Development-Led Industrialization
ATVET	Agricultural Technical and Vocational Education and Training
CC	Climate Change
CC-CGE	Climate Change-Computable General Equilibrium
CE	Certainty Equivalent
CGE	Computable General Equilibrium
CV	Coefficient of Variation
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CSA	Central Statistical Agency
DEC	Development Economics
DFID	UK’s Department for International Development
EDRI	Ethiopian Development Research Institute
EPDRF	Ethiopia’s People Democratic Revolutionary Front
ECHAM	Atmospheric General Circulation Model (European Centre for Medium Range Weather Forecasts
ENSO	El Niño Southern Oscillation
FACE	Free-Air Carbon Enrichment
FAO	Food and Agriculture Organization of the United Nations
FTCs	Farmers Training Centers
GDP	Gross Domestic Product
GC	Government Consumption
GCMs	General Circulation Models
ICPAC	IGAD Climate Prediction and Applications Centre
HadCM3	Hadley Centre Coupled Model, version 3 (GCM)
IDS	Institute of Development Studies (Sussex University)
IPCC	International Panel on Climate Change
IPCC-TGICA	IPCC Task Group on Data and Scenario Support for Impact and Climate Analysis
LES	Linear Expenditure System
LGP	Length of Growing Period
MAMS	Maquette for MDG Simulations (Dynamic CGE Model)
MDG	Millennium Development Goal
MoARD	Ministry of Agriculture and Rural Development
NAPA	National Adaptation Plan of Action
PAGE	Policy Analysis for the Greenhouse Effect
PASDEP	Plan for Accelerated and Sustained Development to End Poverty
PRSP	Poverty Reduction Strategy Paper

R&D	Research & Development
SAM	Social Accounting Matrix
SNNPR	Southern Nations, Nationalities, and People's Region
SRES	Special Report on Emissions Scenarios
SFDCC	Strategic Framework on Development and Climate Change
SSA	Sub-Saharan Africa
TFP	Total Factor Productivity
UNDP	United Nations Development Program
WHO	World Health Organization

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EXECUTIVE SUMMARY

Introduction and Objectives

1. It is now widely recognized that low-income countries in tropical and sub-tropical regions will be disproportionally affected by the adverse impacts of climate change. The combination of already fragile environments, dominance of climate-sensitive sectors in economic activity, and low autonomous adaptive capacity in these regions implies a high vulnerability to the harmful effects of global warming on agricultural production and food security, water resources, human health, physical infrastructure and ecosystems. Recent authoritative scientific assessments emphasize that, even under the most optimistic assumptions about the success of future global mitigation action, an acceleration of adaptation efforts in developing countries over the next decades is essential to build resilience and reduce damage costs.[1]

2. The effects of climate change vary across countries, and adaptation and coping capabilities are influenced by geographical, economic, cultural and political factors. Successful adaptation programs must therefore take into account country-specific circumstances. This pilot study aims to develop a methodology that provides an economy-wide framework for analyzing economic impacts from climate change and potential adaptation policies that developing countries might undertake in the near and long term. To accomplish this objective, the paper modifies and extends a dynamic, single-country prototype Computable General Equilibrium (CGE) model to include stochastic elements that are characteristic of climate change and a representation of the sectors that are most likely to be affected[2].

3. The prototype model is applied to Ethiopia. The country is heavily dependent on rain-fed agriculture, and its geographical location and topography in combination with low adaptive capacity entail a high vulnerability to adverse impacts of climate change. A comprehensive review of the literature on the likely evolution of climate for Ethiopia (or the broader region) underlines the high levels of uncertainty associated with climate change. Regional projections of climate models reasonably robustly predict a substantial rise in mean temperatures over the 21st century. While regional models fairly robustly predict increases in rainfall, higher resolution analyses of Ethiopia suggest a range that spans both increases and decreases in overall rainfall averages. The dispersion in results across models and the models themselves also suggest an increase in rainfall variability with the potential for a rising frequency of both extreme flooding and droughts.

4. For many developing countries, the most important impacts of climate change arise from higher temperatures, increased water stress, and extreme weather events that will most strongly affect agriculture. For Ethiopia, historical data point unequivocally to a strong impact of climate outcomes on agricultural output with both negative and positive deviations from trend. In 2006/07, agricultural production generated around 46 percent of Ethiopia's gross domestic product and employed about 80 percent of the working population. Performance in agriculture also affects performance in other sectors of the economy, so there

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[1] Intergovernmental Panel on Climate Change (2007), Adger et al (2007), Stern (2007).

[2] The he extended model will be designated as CC-CGE throughout.

is a strong observable link between climate change variations and overall economic performance.

Methodology

5. The modelling approach proposed in this study focuses on stochastic elements in general and extreme events in particular. Surprisingly, this focus is relatively new in the economic analysis of climate change. It follows on the work of Hope (2006), who developed the PAGE model. This model provided substantial input into the well-known Stern Report on climate change (Stern, 2007). By placing risk and uncertainty at center stage, the PAGE model illustrates that the potential economic damages from climate change, and hence the potential gains from mitigation and effective adaptation, are much larger than had previously been estimated. As stated recently by Stern (2008, p. 18), "most studies prior to a year or two ago grossly underestimated damages from business as usual." A failure to recognize the potential for significant damages as a result of rare events represented the primary source of this underestimation.

6. The modelling approach described in this paper seeks to build on the considerable advances achieved via the PAGE model. Despite these advances, there remains a great deal to do. In the PAGE model, economic activity is highly aggregate; there are no prices, stochastic realizations are drawn from analytical distributions with assumed parameter values (often the distributions are assumed to be triangular), and the choice of parameters involves "a large amount of judgment to encompass the studies cited by the IPCC." (Hope, 2006, p. 24).

7. The country focus of this study simplifies the modelling requirements in many respects. The PAGE model is a global integrated assessment tool that incorporates both climate science and economics. In the PAGE model, economic choices influence emissions of greenhouse gases, which, over time, influence climate outcomes with, in turn, implications for subsequent economic outcomes. For the analysis considered here, trends in global climate can be taken as exogenous because economic choices in an average size poor country will have minimal impact on global climate. Taking a country perspective, we can disaggregate economic activity by key sectors, account for the role of prices, and consider detailed historical evidence on the economic implications of climate volatility and extreme events on a sectoral basis. Even with a country focus, the fundamental challenges remain of representing highly uncertain future climate changes and their impacts.

8. The approach employed here involves using historical data, but "fattening the tails" of these historical climate distributions in doing impact analysis. This "fattening of the tails" in the subjective prior distribution of future climate outcomes relative to the observed historical distribution comes about for two reasons. First, our high confidence in the existence of climate change combined with our lack of knowledge about the implications of global climate change for climate outcomes in Ethiopia requires us, by information theory, to consider a more uniformly weighted and potentially broader distribution of outcomes. Second, the information that we do have with respect to possible implications of global climate change for Ethiopia points to greater weight at the extremes of the distribution.

9. The critical operational question is exactly how and how much the historical distribution should be modified in order to account for climate change. Our choices for the base climate change scenario, motivated in part by recent work in finance (Weitzman, 2007 and forthcoming), are presented in Table 17, which is reproduced below. The row of Table 17

labelled "Historical" shows a discrete summary of the distribution of estimated climate impacts on agricultural value added. The table divides the distribution of agricultural sector outcomes into six equally weighted parts and presents the mean impact on total value added for each part. The subjective prior distribution of future outcomes, presented in the row just below and labelled "projected", shifts weight to more extreme outcomes.

Table 17: Implications of Climate Outcomes for Total Agricultural Value Added
(% difference from trend by probability tranche)

	Lower					**Upper**
	0<π<1/6	**1/6< π <1/3**	**1/3< π <1/2**	**1/2< π <2/3**	**2/3< π <5/6**	**5/6< π <1**
Historical	-7.3	-3.6	-1.2	1.0	3.0	8.1
Projected	-11.0	-4.1	-1.3	1.6	5.2	11.2

10. While more sophisticated methods for characterizing future distributions are in process, they do not obviate the need for careful consideration of the final subjective prior distribution of future climate outcomes. Like economic models, GCMs are simplifications of reality built to capture the primary forces driving historical realizations. Considerable uncertainty exists as to their performance under conditions of unprecedented (within the domain of historical application of the model) and growing atmospheric CO2 concentrations. Furthermore, while significant effort has been expended to determine the likely mean impact of greenhouse gases, less effort has been expended in representing extreme events. And, extreme events are more difficult to characterize precisely because they are rare. Consequently, while improved information about the likely distribution of future climate outcomes is always desirable, the need to develop a subjective prior distribution of future climate outcomes will remain.

11. Before presenting results of the modelling, it is worth emphasizing that the focus of this initial pilot study is primarily on methodology development. While some policy recommendation can be derived from the work conducted to date, rigorous quantitative analysis of alternative adaptation policy options is needed to support the formulation of more specific policy recommendations.

12. Six experiments are reported and discussed, a deterministic base run and five stochastic scenarios--over a 25 year simulation horizon, which are designed to demonstrate the feasibility and robustness of the modelling methodology. The simulations are designed to explore the potential negative impact of climate shocks, in the absence of investments designed to ameliorate them. The six experiments are:

- Base run with deterministic outcomes—no stochastic shocks. Exogenous labour force and land growth, and exogenous trends on productivity growth in all sectors.
- Sim 1: Historical pattern of agricultural productivity variability, drawing sectoral agricultural productivity shocks due to climate shocks from the historical record.
- Sim 2: Increased variance of agricultural productivity shocks by increasing the weight of extreme shocks in sampling from the historical record. Standard deviation of productivity shocks increases by 41%. Essentially no shift of mean.
- Sim 3: Sim 2 plus negative 5% shift in the mean of productivity shocks.
- Sim 4: Sim 3 plus increased standard deviation of shocks by 34% (multiplying each shock by 1.34, increasing variance by 80%).

- Sim 5: Sim 2 plus negative 10% shift in mean productivity shocks and increased variability only of negative shocks (multiplying each negative shock by 1.34).

13. In the stochastic scenarios (Sims 1-5), climate shocks are assumed to have asymmetric impacts on productivity and sectoral capital stocks. A positive climate shock in a given year and agricultural sector increases sectoral factor productivity. A negative shock to productivity in a particular agricultural sector is assumed to result in a decrease in the rate of growth of productivity in that year and also in the destruction of the some of the installed capital in the sector. In effect, the negative climate shock is assumed to result in additional depreciation of sectoral capital for the year in which the shock occurs, which results in less aggregate growth of the capital stock for a given level of investment than would otherwise have occurred.

14. The first stochastic simulation, Sim 1, essentially reproduces the historical stochastic experience of Ethiopia, and the results compared to the base run indicate the importance of using a stochastic rather than a deterministic model. The remaining simulations assume various impacts of climate change. The second, Sim 2, employs the projected distribution summarized in Table 17 The third, Sim 3, shifts the distribution away from the historical record, assuming a 5% negative shift in the mean of the agricultural productivity shocks in addition to increased sampling weight on extreme shocks, as in Sim 2. Simulations 4 and 5 also start from Sim 2, but postulate different changes in the historical distribution. Sim 4 shifts the mean as in Sim 3, and also assumes increased variability. Sim 5 assumes a larger negative shift in the mean of the shocks (negative 10%) and increased variability of the negative shocks. The assumed negative mean shifts are broadly in the range suggested by the predictions of Ricardian and crop simulation studies reviewed in section 5.

Key Findings

15. Table 19, reproduced below, provides aggregate growth rates. The base run generates a 7.48 percent average annual real GDP growth rate over a 25 year simulation horizon. The various climate shocks lower these growth rates significantly, especially with shifts of the mean to negative shocks. The historical record with more variation, Sim1, has a relatively minor impact on growth rates—if the future is like the past, but with just increased variation, the impact of climate shocks on average growth rates is modest. The impact on variation of growth rates, however, is significant. As the variance increases and the shocks become more negative, the impact is much more serious. The worst case scenario, Sim5, results in growth rates two and a half percentage points lower than in the deterministic base run. Lower growth rates cumulate through time. In the worst case scenario, real GDP in the final year would be 46 percent lower than in the base run.

16. Analysis of the variability of the components of GDP indicates that aggregate consumption always has a higher coefficient of variation (CV) than the other macro aggregates. The burden of adjustment appears to fall more heavily on consumers. This is to be expected since the productivity shocks all occur in agriculture, most of which is used for consumption. Further, the CV for aggregate absorption is always smaller than for real GDP, indicating that international trade serves to dampen the impact of climate shocks on aggregate demand.

17. Sectoral analysis was also undertaken. While the productivity shocks occur only in the agricultural sectors, the negative impact is spread across the economy. The results

indicate the importance of using an economy-wide framework for analyzing the impact of climate change shocks, even if the shocks are largely focused on a few sectors. The indirect effects arising from productivity shocks are as important as the direct effects.

Table 19: Growth Rates of Real Macro Aggregates

Macro Aggregates	Base	Sim1	Sim2	Sim3	Sim4	Sim5
Consumption	6.93	6.63	6.54	5.42	5.35	4.18
Investment	7.49	7.25	7.19	6.07	6.01	4.78
Government	6.41	6.27	6.23	5.43	5.40	4.53
Exports	10.09	9.79	9.70	8.24	8.17	6.58
Imports	6.95	6.69	6.61	5.39	5.33	4.07
Absorption	6.96	6.69	6.63	5.55	5.49	4.35
GDP	7.48	7.19	7.13	6.01	5.94	4.75

Note: *Base:* baseline simulation in the absence of any climate-related shock. *Sim1*: historical sample distribution. *Sim2*: double historical variance plus negative 20% shift of mean. *Sim3*: 25% increase in Sim2 shocks plus 25% negative shift of mean. *Sim 4*: Sim 3 plus increased standard deviation of shocks by 34%. *Sim 5:* Sim 2 plus negative 10% shift in mean productivity shocks and increased variability only of negative shocks

18. The simulation results indicate that effective adaptation measures are vital if Ethiopia is to sustain the per-capita growth rates required for achieving the Millennium Development Goals. Adaptation policies designed to reduce vulnerability to climatic change are more likely to succeed if they are integrated with efforts aimed at poverty reduction and general economic growth strategies. Ethiopia's high level of unexploited water resource management potential and low fraction of irrigated land suggest that investments in water resource management infrastructure should be an integral component of a climate change adaptation strategy aimed at the reduction of vulnerability to the effects of global warming. However, a rigorous quantitative analysis of alternative adaptation policy options that would allow the formulation of specific policy recommendations requires further in-depth research into the expected costs and potential benefits of specific adaptation measures and is beyond the scope of this report.

19. It would be feasible in the CC-CGE model to introduce alternative technologies for the various agricultural sectors that are more resistant to the impact of climate shocks. Such technologies would undoubtedly be more capital intensive, and also intensive in the use of intermediate inputs. By directing investment into these sectors, the model would capture the potential tradeoffs from adopting technologies that are more resistant to climate shocks, but that are more expensive.

20. All these modelling strategies do not require modelling of the explicit links between particular climate shocks such as changes in average temperature and/or rainfall and economic performance in agriculture. One can use indirect measures of the links through econometric analysis, as done in the studies cited above. Moving toward more detailed

models requires disaggregation by crop and agro-climatic region (or watershed), as well as studies of the links between changes in measurable climate variables and agricultural outcomes. Such analysis would greatly enhance our ability to incorporate investment in new adaptation measures into formal models. Since there is little or no historical experience with such measures, it is impossible to estimate their impact using econometric analysis of historical data. A modelling strategy that incorporates engineering and agronomic analysis, rather than summary econometric relationships, is likely to be very fruitful.

1. INTRODUCTION

1.1 Background

21. It is now widely recognized that developing countries—and in particular low-income countries in tropical and sub-tropical regions—will be disproportionally affected by the adverse impacts of climate change. The combination of exposure to an already fragile environment, dominance of climate-sensitive sectors in economic activity and low autonomous adaptive capacity in these regions entail a high vulnerability to the harmful effects of global warming on agricultural production and food security, water resources, human health, physical infrastructure and ecosystems. Recent authoritative scientific assessments emphasize that even under the most optimistic assumptions about the success of future global mitigation action, an acceleration of adaptation efforts in developing countries over the next decades is essential to build resilience and reduce damage costs.[3]

22. Effective adaptation programs need to be comprehensive and integrated with overarching national strategies of individual countries, identify and exploit synergies, while balancing trade-offs between sustainable development, risk reduction and adaptation policy objectives. Such initiatives also require new and sustained funding sources. The effects of climate change vary across countries and adaptation and coping capabilities are influenced by geographical, economic, cultural and political factors. Successful adaptation programs must therefore take into account country-specific circumstances.

23. As part of the implementation of the World Bank's Strategic Framework on Development and Climate Change (SFDCC) (World Bank, 2008a) and its climate change strategy in Sub-Saharan Africa (World Bank 2008b), as well as a wider new World Bank initiative to provide analytical support for the mainstreaming of climate change in development policies, this pilot study aims to develop a methodology that would provide an economy-wide framework for analyzing economic impacts from climate change and potential adaptation policies that developing countries are likely to undertake in the near and long term. To accomplish this objective, the paper modifies and extends a dynamic single country proto-type Computable General Equilibrium (CGE) model to include stochastic elements that are characteristic of climate change and a representation of the sectors that are most likely to be affected.

24. Ethiopia has been chosen as the first case study for developing the new prototype modeling framework. A number of factors have motivated this choice. Ethiopia is heavily dependent on rain-fed agriculture, and its geographical location and topography in combination with low adaptive capacity entail a high vulnerability to adverse impacts of climate change. Regional projections of climate models do not only predict a substantial rise in mean temperatures over the 21st century but also suggest an increase in rainfall variability with a rising frequency of both extreme flooding and droughts due to global warming. Agricultural sector performance also affects performance in other sectors of the economy. Hence, there is a strong observable link between climate change variations and overall economic performance. In recognition of the pervasive influences of climate change, the country's policy plans explicitly outline various adaptation and coping measures, whose effectiveness must be evaluated. The study is facilitated by the availability of a Social

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[3] Intergovernmental Panel on Climate Change (2007), Adger et al (2007), Stern (2007).

Accounting Matrix (SAM) for 2001/2002 recently constructed at the Ethiopian Development Research Institute (EDRI) in collaboration with the Institute of Development Studies (IDS) that provides an empirical basis for analyzing climate change issues. The goal is to provide a consistent and flexible comparative analytic framework that can be adapted to other case study countries in the second phase of the wider World Bank initiative.

25. The terms of reference for this study are based on the premise that for many developing countries, the most important impacts of climate change arise from higher temperatures, increased water stress, and extreme weather events that will most strongly affect agriculture. These effects can be modeled through a dynamic series of productivity shocks that are sector-and country-specific, for example based on the Ricardian approach proposed by Mendelsohn et al (1994). The impacts on productivity can be calibrated to the country-specific climate impacts on temperature and rain as projected by the various general circulation models (GCMs). Extreme weather events could lead to the destruction of infrastructure and capital, either temporarily or permanently. Impacts on health could be modeled as declines in labor productivity and increases in mortality, again calibrated to existing local studies where they exist.

26. Some of the adaptation mechanisms, particularly private actions, can be incorporated endogenously into models. For example, farmers will crop-switch based on the relative productivity impacts and changes in price signals. The results are likely to show acceleration in rural to urban migration as agriculture takes a relatively larger hit than other sectors. Other adaptation mechanisms can be treated as exogenous policy shocks; for example, new investment to reinforce or expand infrastructure and additional expenditures on health care. To the extent these adaptation policies can be costed (as a separate exercise), it will be possible to assess the financial and economy-wide impacts from implementing these at the level of general budgetary expenditures.

27. One key area to be explored is the role of uncertainty. Incorporating stochastic elements in climate change models is important, given that the impacts are described in the scientific literature in terms of changes in means and variances of weather variables. Another avenue that needs to be pursued is the role of threshold effects associated with extreme weather events. For example, catastrophic events have asymmetric effects on the economy. Droughts typically lead to a cyclical downturn in outcomes but with a reversion to mean when rains return. Floods or severe storms, on the other hand, can destroy infrastructure and a reversion to mean only occurs with new infrastructure investment over time.

28. The focus of the modeling approach proposed in this study is correspondingly on stochastic elements in general and extreme events in particular. Surprisingly, this focus is relatively new in the economics of climate change. It follows on the work of Hope (2006), who developed the PAGE model. This model provided substantial input into the well known Stern Review on climate change (Stern, 2007). By placing risk and uncertainty at center stage, the PAGE model illustrates that the potential economic damages from climate change, and hence the potential gains from mitigation and effective adaptation, are much larger than had previously been estimated. As stated recently by Stern (2008, p. 18), “most studies prior to a year or two ago grossly underestimated damages from business as usual.” A failure to recognize the potential for significant damages as a result of rare events represented the primary source of this underestimation.

29. The modeling approach described in this paper seeks to build on the considerable advances achieved via the PAGE model. Despite the advances, there remains a great deal to do. In the PAGE model, economic activity is highly aggregate, there are no prices, stochastic realizations are drawn from analytical distributions with assumed parameter values (often the distributions are assumed to be triangular), and the choice of parameters involves "a large amount of judgment to encompass the studies cited by the IPCC." (Hope, 2006, p. 24).

30. The country focus of this study simplifies the modeling requirements in many respects. The PAGE model is a global integrated assessment tool that incorporates both climate science and economics. In the PAGE model, economic choices influence emissions of greenhouse gases, which, over time, influence climate outcomes with, in turn, implications for subsequent economic outcomes. For the analysis considered here, trends in global climate can be taken as exogenous because economic choices in an average size poor country will have minimal impact on global climate. This frees analytical resources and allows for disaggregation of economic activity by key sectors, to account for the role of prices, and to consider historical evidence on the economic implications of climate volatility and extreme events on a sectoral basis. These features are accomplished. Nevertheless, the fundamental challenge of representing a highly uncertain future climate distribution remains. The approach employed here involves "fattening the tails" of historical climate distributions. This approach is consistent with the most recent analytical contributions to the economics of climate change with a focus on risk and uncertainty (Weitzman, forthcoming).

1.2 Scope of the Report

31. The report is organized as follows: Section 2 provides a brief overview of the Ethiopian economy, its recent growth performance, and economic development strategies, particularly its coping and adaptation policies towards the impacts of climate change. Section 3 provides a summary of relevant topographic and climatic background information for the country. Section 4 summarizes medium- and long-run projections of climate change for East Africa and Ethiopia. Section 5 reviews existing region-specific estimates of climate change impacts on agricultural productivity, covering both studies based on the Ricardian approach and process-based crop simulation model results. This section also discusses potential yield impacts arising from increased variability in climatic variables and from an increased frequency of extreme weather events. This review informs the selection of the general order of magnitude for the mean shifts in agricultural productivity used in the dynamic stochastic simulation analysis in Section 8. Section 6 turns briefly to potential climate change impacts that may affect the long-run growth performance of the Ethiopian economy through channels other than agricultural productivity. Section 7 provides an overview of the dynamic CGE model and outlines the proposed simulation methodology including the treatment of uncertainty. A detailed technical documentation of the model is given in Appendix C. Section 8 presents the results of the dynamic stochastic climate change impact analysis. This section also identifies a potential range of adaptation policy measures for inclusion in envisaged future extensions of the dynamic simulation approach proposed here.

32. It is worth emphasizing that the focus of this initial pilot study is primarily on methodology development. A rigorous quantitative analysis of alternative adaptation policy options that would allow the formulation of specific policy recommendations requires further in-depth research into the expected costs and potential benefits of adaptation measures and is beyond the scope of this report. Further efforts in this direction are envisaged for the Ethiopia country case study in the second phase of the wider World Bank research initiative.

2. OVERVIEW OF THE ETHIOPIAN ECONOMY

2.1 Basic Characteristics

33. With around 75 million inhabitants, Ethiopia is the second most populated country in Sub-Sahara Africa (SSA). Despite rapid economic growth over the past five years, per capita income—$255 in 2006/07 at current prices—remains well below the SSA average. The 2006/07 share of agriculture in GDP is 46 percent while industry accounts for 13 percent and services for 41 percent (CSA, 2008). The main export commodity is coffee with a share of 35.7 percent in total merchandise exports 2006/07 followed by oil seeds (15.8%), gold (8.2%), chat (7.8%), leather and leather goods (7.5%) and pulses (5.9%) (IMF, 2008). Ethiopia is a net importer of wheat. Petrol, coal and gas are only imported, capital goods have very high import shares, and a number of consumer goods also have high import shares.

34. Given the importance of agriculture for the Ethiopian economy and its key role in the transmission of climate shocks, the following outlines the main characteristics of this sector and its contribution to recent economic growth. A brief historical overview of the evolution of land tenure in Ethiopia is provided in Appendix A.

2.2 The Agricultural Sector and Recent Growth Performance

35. The role of agriculture and rural development for growth and social welfare are increasingly considered as key elements of a development strategy for an economy with weak manufacturing sector and no significant natural resource base like petroleum. Research also shows the role of agricultural incomes as a source of effective demand for domestic manufacturing through the analysis of linkage effects.[4] Given this reality, the government—Ethiopia's People's Democratic Revolutionary Front (EPDRF) that emerged in 1991 after winning a seventeen-year guerrilla war against the Marxist military junta that reigned the country since 1974—advocated for a market oriented economy and began to undertake reforms to improve the agriculture sector. The initial reforms included disbanding the price control system that compelled farmers to sell their produce at predetermined rates to the State and instituting an agriculture development led industrialization (ADLI) policy as the overarching guide to addressing the fundamental problems of the sector. Hence, under the ADLI framework, a number of focused policy actions were taken to enhance agricultural productivity and ensure food security. Despite these efforts, fast rural population growth in combination with other factors detailed below has led to severe environmental degradation. Deforestation and, soil erosion have increasingly become more pronounced over the past decade, in part due to the poor performance of other sectors to absorb the growing population.

36. In 2006/07, agricultural production generated around 46 percent of Ethiopia's gross domestic product and employed 80 percent of the working population. According to Deressa (2006), about 16.4 million ha—that is 14.6 percent of Ethiopia's total land area—is arable land, of which about 8 million ha is currently used for crop production. The agricultural sector is dominated by mixed rain fed small-scale farming based on traditional technologies. Small-scale subsistence farming (about eight million peasant households) accounts for 95% of the total area under crops and for more than 90% of the total agricultural output. Most food

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[4] Mellor (1986); Hazell and Ramasamy (1991), Adelman (1984).

crops (94%) and coffee (98%) are produced by small-scale farmers, while the remainder is generated by private and state commercial farms. Production technologies are predominantly characterized by the use of ox-drawn wooden ploughs with steel pikes and other traditional farm implements, minimal application of fertilizer and pesticides due to high input prices in the presence of credit constraints[5] and weak extension services, and low use of improved seeds (Deressa, 2006).

37. By the end of 2005/06 fiscal year, only 13 percent of the potentially irrigable land area was irrigated (Table 4). A typical farming household in the semi-arid areas owns just a small portion of land (generally less than one hectare) for crop and livestock (cattle, goats, sheep, poultry, donkeys) production. In addition to these constraints, the country continues to experience persistent drought episodes because of its prominent location in the Sahel Region, a region with erratic rainfall and unpredictable climatic variability. Factors contributing to the low productivity of the agricultural sector besides droughts and floods include declining farm sizes due to population growth, land degradation due to inappropriate use of land such as cultivation of steep slopes, over cultivation and overgrazing, tenure insecurity, weak agricultural research and extension services, lack of agricultural marketing, an inadequate transport network, low use of fertilizers, improved seeds and pesticides, poor nutrition of livestock, low level of veterinary care, and livestock diseases. Table 1 provides information on the commodity composition of agricultural output.

Table 1: Product Shares in Total Agricultural Value Added and Output 2001/02

Agriculture Outputs	*Percentage Share in Value Added*	*Agricultural Gross Output*
Livestock	16.5	15.3
Fruits and vegetables	15.7	14.5
Maize	13.1	13.3
Pulses	12.0	11.5
Coffee	10.4	11.0
Other Cash Crops*	5.6	5.1
Wheat	4.6	5.0
Barley	3.8	3.8
Teff	2.3	3.2
Oil Seeds	1.6	2.0
Other Crops	1.1	2.5
Forestry and Fishing	13.1	12.7

Source: Social Accounting Matrix 2001/02 - EDRI (2008).
Note: *Other cash crops comprise (ordered by output value): Plant-based fibers, raw cotton, chat, tea, sugar cane.

38. A large proportion of the farm output is consumed at home as own consumption. As recently as 2001/02, the Central Statistical Agency's (CSA) agriculture census estimated that farmers consumed at home about 63 percent of their total output, and that less than 30 percent

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[5] Using a nationally representative data set, Croppenstedt, Derneke and Meschi (2003) identify credit constraints and low value-cost ratios due to high procurement and distribution costs as major hurdles to the adoption and intensity of fertilizer use in Ethiopia.

was in fact marketed.[6] Although several factors may be cited as possible reasons for the high share of own consumption among Ethiopian farm households, two of the main factors are the low development of the country's infrastructure and the low prices farmers fetched for their produce until recently.

39. In addition to the poor and inadequate infrastructure, prices fetched by farmers were historically very low. For instance, domestic prices of tradable cereals for the most part were well below the parity prices of imports until April 2008. Again, although several factors may be attributed, weak consumption demand at the macro-level and the marketing practices of farmers at the micro-level may be cited as the primary reasons.

40. Consumption demand was very weak prior to 2003/04. For instance, between 1995/96 and 2002/03, it grew by a mere 19 percent, far lower than the 46 percent growth it recorded in the next three years (2003/04 – 2005/06) under a robust annual average economic growth rate of above 10 percent. To be sure, in any given year throughout the last decade, about seven million people on average were chronically food deficient and needed assistance. Nevertheless, this food need did not constitute demand due to a lacking ability to pay. Therefore, much of this need was met through food aid imports, which the country continually received in successive years. For instance, in 2001 and 2002, more than 938 thousand MT of wheat was imported into the country by donors. Since 2005, however, increased use of domestic grain purchase and direct cash transfers as means of supporting food insecure area residents of the country have resulted in lower demand for and reliance on wheat imports as aid.

41. The other main factor that depressed prices was the marketing practice of farmers that prevailed in the country for quite a long time. Historically, food prices typically followed a well established pattern where prices fall during the months of November to March and climb back again during the lean months of June to September. This price pattern is linked to the marketing behavior of farmers. Farmers sell their produce early at low prices in order to settle debt and for other necessities (distressed selling) and buy food and seed at higher prices later in the lean seasons. Typically farmers finance this cycle through borrowing from various private sources during the plowing and sowing periods, repaying after harvest.

42. Distress selling and high credit costs lock farmers into a vicious cycle of borrowing to cover production costs and consumption during the lean season, and being forced to sell at low prices to repay debts at harvest. The unavailability of off-farm employment activities in rural Ethiopia until very recently contributes to the problem, since farmers are unable to diversify their income sources.[7] Furthermore, given the erratic rainfall pattern, during the period of its inevitable failure, even farmers in some of the most productive parts of the country become destitute and are often forced to sell productive assets like their oxen. By the time the rains come again, these farmers become unable to farm and therefore face severe food shortages. Distress selling by farmers is perhaps the major cause of the depressed prices they received. It also amplifies the impacts of droughts and other climate changes on rural households due to their low coping capabilities. As a result of these factors, agriculture sector productivity has traditionally been very low.

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[6] CSA (2003).

[7] Ahmed (2007).

43. There has been encouraging progress in economic growth in recent years, however, which in turn is beginning to improve many aspects of life in the country. There are also several indications that the economy is undergoing major structural changes. As indicated in Table 2, economic performance measured by growth in real GDP has been rising in the past five years, jumping to an annual average rate of more than 10 percent during 2003/04 – 2007/08.

Table 2: Real GDP Performance

Average Growth Rate 1997/98 – 2002/03	Average Growth Rate 2003/04 – 2006/07
2.23%	**11.28%**

44. Performance in the non-agricultural sectors was strong compared to previous trends. The four year annual average growth of value added in manufacturing was above 10 percent, while public sector value added, particularly education and health sectors during the same period, registered an annual average growth rate of 11.6 and 11 percent respectively. Different service sectors also grew by an average of 10 to 20 percent.

45. Although the present high growth performance is broad-based, it is successful agriculture that is providing a major driver. Between fiscal years 2003/04 and 2006/07, the annual average growth rate for real agricultural value added was above 13 percent. Furthermore, the price farmers fetched for their produce have begun a steady rise since the beginning of 2006. For instance, the March 2008 Agriculture Producer Price Index has risen by above 86 percent relative to its January 2006 levels.[8]

46. Except in the 2007/08 fiscal year when the *belg* or the minor rainy season failed, the past four years were relatively free from exogenous shocks associated with adverse climatic changes and the consequential harvest failures. Furthermore, the *belg* rainy season typically accounts for less than 10 percent of total output. Therefore, the good successive rainy seasons are one of the reasons for the relatively strong performance of the agriculture sector, and as a consequence the entire economy.

47. Despite strong agriculture and non-agriculture sectors performance as in the past five years (Table 3), any failures of the rains threaten the performance of the economy as a whole and cause severe malnutrition and loss of livelihoods for households in marginal and less productive lands. This demonstrates that economic growth in general and households' welfare in particular are still significantly influenced by rainfall and climate variation. The fact that rainfall is quite erratic places an enormous burden on the economy and complicates policy attempts to tackle its challenges.

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[8] Figure based on EDRI calculations.

Table 3: Average Growth Rate for Real Agriculture Value Added

Agriculture & Individual Sectors	Average Growth Rate 1997/98 – 2002/03	Average Growth Rate 2003/04 – 2006/07
Agriculture & Allied Activities	-1.14%	13.18%
Crop	-2.08%	18.01%
Animal Farming and Hunting	-0.05%	5.57%
Forestry	2.70%	2.69%
Fishing	4.70%	5.13%

2.3 Current Policies in Support of Agricultural Development, Economic Growth and Poverty Reduction

48. Poverty reduction reduces vulnerability to climate variability. The Ethiopian government prepared and adopted two successive poverty reduction strategy programs (PRSP). The first was the Sustainable Development and Poverty Reduction Program (SDPRP) that covered three years (2000/01-2003/04) and the second is a five year (2005-2010) guiding strategic framework known as Plan for Accelerated and Sustained Development to End Poverty (PASDEP).

49. Policies such as human development, rural development, food security, and capacity-building that were a priority in the SDPRP were augmented under the PASDEP. In addition to these, however, new strategic directions with emphasis on commercialization of agriculture and an emerging urban agenda are also pursued as means to mitigate the challenges faced by the agriculture sector and the overall economy.[9]

50. The agricultural strategy revolves around a major effort to support the intensification of marketable farm products by both small and large farmers. To help jump-start this process, a range of public investments are identified and being implemented. The major investments include the construction of farm-to-market roads and area irrigation through multi-purpose dams. Other related services also include measures to improve land tenure security, reforms to improve the availability of fertilizer and improved seeds, and specialized extension services for differentiated agricultural zones and types of commercial agriculture.[10]

51. The investments on roads is formulated under a Road Sector Development Program that begun in 1997 and is presently in its third phase (2007 – 2012). The program targets the construction of almost 20,000 km. of new roads by 2010, where 90 percent of them are in rural areas. The expansion of the road network also includes improved maintenance so that 84 percent of the network is in good condition.[11]

52. Although increasing access to markets through improved road networks is a critical aspect of enhancing the agriculture sector performance, increasing yields for basic grains would also require sustained investments in irrigation and better use of ground water. Availability of water in adequate and regular pattern also influences the use of technologies such as fertilizers, chemicals and improved seeds, as their use is positively and strongly

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[9] MoFED (2005).

[10] MoFED (2005).

[11] Ethiopia Roads Authority (2006).

correlated with the availability and adequacy of water resources. Therefore, one of the major investments being implemented is in rural water supply, which is being expanded to reach 85 percent of the population by 2010. Moreover, construction of 1870 deep wells, 12,755 shallow wells, and 101,355 hand-dug wells, 420 ponds, 780 cisterns and 15 surface water sources and 11,445 spring development as well as 47,399 schemes rehabilitation works is also being undertaken.

53. A major effort is also being made to promote and strengthen small-scale irrigation schemes such as river diversion, micro-dam construction, ground water abstraction for supplementary and double cropping, through provision of technical and material support for expansion and improved water use efficiency. Effort is also being made to strengthen water harvesting and utilization practices through provision of appropriate technologies for supplementary irrigation and promoting low-cost manual, mechanical and electrical water lifting mechanisms; and the mini-drip irrigation method and family drip-kits.[12] In addition, medium- and large-scale irrigation projects are being promoted. For instance, plans during the PASDEP period include, construction of 24 identified projects covering an area of 322,630 ha., the feasibility study and design of 19 projects (229,149 ha) and pre-feasibility of seven others (117,116 ha).

Table 4: Irrigation Potential and Existing Irrigation Schemes

Irrigation Potential	**Total Small Scale Irrigation Implemented (including traditional & modern)**			**Medium & Large Scale Irrigation Implemented**	**Private Implemented**
(million ha)	2004/05 (ha)	2005/06 (ha)	Total – end of 2005/06 (ha)	(ha)	(ha)
4.25	306,702	242,843	549,545	61,057	5,414

Table 5: Number of Water Harvesting Structures/Ponds Constructed Since 2002/03 in the Four Major Regions of Ethiopia

Region	**Number**
Tigray	114,900
Amhara	327,670
Oromia	267,039
SNNPR	242,511
Total	952,120

Note: The water harvesting structures include hemispherical, trapezoidal and community ponds as well as hand dug wells. The capacity of ponds varies from 60,000 liters to 180,000 liters.

54. Associated with water resource use is the generation of energy by constructing renewable hydro-electricity generating dams. Presently, five hydro-electric dams and one

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[12] MoFED (2005).

wind farm are under construction. When finalized, they are expected to increase power supply to a total of 3270 MW and provide access to 50 percent of the total number of households in the country. Moreover, the hydro-electric generating dams are also expected to regulate water flows, control floods and channel water for irrigation purposes.

55. Among the five dams being undertaken, the Tekeze, Gilgel Gibe II, Amerti-Neshi and Beles projects are expected to be finalized by 2009, while Gilgel Gibe III is in the early stages of implementation and is not expected to be operational before 2012.

Table 6: Dams and Wind Farms Under Construction

	Electricity Generation Capacity	
Dams Under Construction	**MW**	**GWh**
Tekeze Hydro Electric Power Plant	300	971
Gilgel Gibe II Hydro Electric Power Plant	420	1,600
Amerti Neshi	100	215
Wind park	120	
Beles	460	1,540
Gilgel Gibe III	1,870	
Total	3,270	4,326

Source: Ethiopian Electric Power Corporation (EEPCO).

56. A further notable policy effort to support agricultural development is providing farmers access to credit at favorable terms so that they can maintain liquidity to purchase farm inputs and diversify their asset base (e.g., by raising livestock). The credit access is channeled through micro-finance institutions and through other arrangements coordinated by the Ministry of Agriculture and Rural Development (MoARD) and regional agriculture offices. Micro-finance credit started in earnest in 2001 with 23 regionally organized finance institutions. By December 2001 the institutions had a total of 461,326 clients. By December 31, 2006 the number of lending institutions had risen to 26 and the total number of clients to well over 1.5 million. As of June 2007, the number of clients has further increased to about 2.5 million. The outstanding loan portfolio and savings balance have also increased from 308 million birr in loans and 243 million birr in savings in December 2001 to almost 2.2 billion birr in outstanding loans and more than 816 million birr in savings by December 31, 2006. The total outstanding loans have also risen to well over 3 billion birr at the end of June, 2007.

57. As part of its agricultural extension program, the government has embarked on the construction of Farmers Training Centers (FTCs) across rural Ethiopia. The plan was launched in 2004/05 with the target of constructing one Farmers Training Center in each rural *Kebele* of the country. In total, 15,000 – 18,000, FTCs are planned for construction. At the end of the 2006/07 fiscal year, a total of 7,401 FTCs have been established. In each Farmers Training Center, three Development Agents (Das) are assigned to provide training to the farmers and pastoralists in three major areas of crop production and protection, livestock development and health, and natural resource management. In addition to the Development Agents, two experts for every three Farmers Training Centers (FTCs) are assigned to provide veterinary service and co-operative support.

58. Two levels of agricultural technical and vocational education and training (ATVET) are being pursued. The FTCs are providing farmers with training of 2-3 months on specialized technologies and techniques (for example water-harvesting or sericulture) for which modules have been developed. At the broader level, 25 technical colleges and training institutes nationally are providing a three year intensive training of 55,000 extension agents. Of these, 45,000 will be placed at FTCs to provide direct support to farmers; 5,000 will provide veterinary services, and 5,000 will support cooperatives. The plan is that this intensive ATVET effort will be completed by 2010, and the colleges will then shift on to short-term training, skills upgrading, and outreach.

59. The investments in the sector could very well extend the present performance of the agriculture sector in the coming years, and in turn drive overall growth in the short term due to its large linkage effects in the economy. Particularly commercialization of smallholder agriculture is poised to gather momentum.

3. TOPOGRAPHICAL AND CLIMATIC BACKGROUND

60. Ethiopia is located between 3.5° - 15°N latitude and 33° - 48°E longitude in North-Eastern Africa with an area of about 1.1 million square kilometers. Around 45 percent of Ethiopia consists of a high plateau with mountain ranges divided by the East African Rift Valley. Almost 90 percent of the population resides in these highland regions with elevations greater than 1500m above sea level. The surrounding lowlands (<1500m) are mostly populated by pastoralists. Ethiopia's varied topography is associated with three main climatic zones (Figure 1) or three agro-ecological zonal divisions collectively know as the "three Ethiopias".

3.1 The "Three Ethiopias"

61. Traditionally, Ethiopian farmers have always recognized at least three major agro-climatic zones based on the relation between elevation and temperature. These traditional agro-climatic zones were known as *Kolla* (warm semiarid), <1500m above sea level, *Woinadega* (cool sub-humid temperate zone), 1500-2400m above sea level, and *Dega* (cool and humid zone) mostly >2400m above sea level. As the population increased and agricultural activities expanded, two more were added at the extreme ends of the climatic conditions. These were *Bereha* (hot arid) and *Wurch* (cold and moist).

62. In recent years, however, a more comprehensive characterization of the agro-ecological zones of the country was developed based on precipitation and temperature, the two major climatic elements that play important roles in the determination of the biomass density, productivity, and community composition and distribution of species in any agro-ecological zone.[13] Precipitation and temperature are then linked with interrelated physical, abiotic and biotic parameters of physiography, soils, vegetation, animals, and human activities.

63. The latest and comprehensive agro-ecological zone classification developed at the Ministry of Agriculture and Rural Development (MoARD) primarily focuses on potential productivity of the particular zone and secondly on species composition and distribution of the plant community. Although biomass productivity is the function of climate, soil, and management, the major environmental factor or characteristic which influences biomass growth, density and productivity is the availability of moisture which satisfies evaporation and transpiration requirements provided that other environmental factors are not limiting. The composition of both botanical and animal colony is often determined by a number of factors, although precipitation and temperature exert major influences in determining the colony's composition. It is therefore very important that the two limiting climatic elements, the number of days in which adequate moisture is available for growth and development of plants and conducive temperature for adaptation are given high priority and due consideration. Thus, these were major guiding principles used for the classifications and calibration of the agro-ecological zones developed by MoARD.

64. The moisture availability periods in days for the entire country was assessed based on long term rainfall data representing durations from 15 to 30 years or more. Moisture availability for plant growth was assessed using the water balance model by incorporating the

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[13] MoARD (2000).

concept of soil water holding capacity representing conditions in Ethiopia. The assessment, however, gave more attention to the length of growing period (LGP) concept which took care of the mean monthly rainfall and mean monthly evapotranspiration relationships.[14] The onset, end and duration of length of growing periods in terms of mean and median values were statistically determined.

65. Rainfall patterns in Ethiopia are both bimodal and unimodal. In the agro-ecological zones classifications and characterizations study, however, due emphasis was also given to the analysis and distribution assessment of these patterns as they have significant impact on crop growth and development of an area. For agricultural planning purposes, the concept of dependable growing period was introduced which is defined as minimum period that can be expected in 4 out of 5 years with significant moisture for optimal plant growth.

66. The agro-ecological zones of the MoARD study were delineated under 18 agro-ecological zones based on temperature and moisture regimes classification. However, owing to the fact that rainfall reception largely determines the economic performance of the country, the 18 agro-ecological zones were grouped into three different parts based on rainfall reception, effectively determining the current "three Ethiopias" classifications. The following table lists the criterion used to identify and characterize the Agricultural Extension Division and thus the "Three Ethiopias".

Table 7: Agricultural Extension Division: "Three Ethiopias"

Criterion for the Three 'Ethiopias' Classification					
Agricultural Extension Division	**Major AEZ's**	**Length of Growing Period (LGP) (Day)**	**Rainfall Reception in mm**	**Thermal Zone in degree C**	**Altitude in meters**
Nomadic Pastoralist	A1	< 45	< 300	> 21	< 1600
	A2	< 45		11-21	1600-3200
	SA1	46-60		> 21	< 1600
	SA2	46-60		11-21	1600-3200
Drought Prone areas with inadequate and unreliable rainfall	SM1	61-120	300-700	> 21	< 1600
	SM2	61-120		11-21	1600-3200
	SM3	61-120		< 11	> 3200
	M1	121-180		> 21	< 1600
	M2	121-180		11-21	1600-3200
	M3	121-180		< 11	> 3200
Moisture Reliable	SH1	181-240	> 700	> 21	< 1600
	SH2	181-240		11-21	1600-

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[14] LGP is by definition a continuous period during the year when the precipitation is greater than one half of the evapotranspiration. See MoARD (2000) for further details.

					3200
	SH3	181-240		< 11	> 3200
	H1	241-300		> 21	< 1600
	H2	241-300		11-21	1600-3200
	H3	241-300		< 11	> 3200
	Ph1	> 300		> 21	< 1600
	Ph2	> 300		11-21	1600-3200
Source: Ministry Of Agriculture and Rural Development Extension Department. Rainfall Reception criterion is added to the original table.					

Table 8: Major Agro-Ecological Zones

Symbols	Universal Terminologies
A1	Hot to warm arid lowland plains
A2	Tepid to cool arid mid highlands
SA1	Hot to warm semi-arid lowland plains
SA2	Tepid to cool semi-arid mid highlands
SM1	Hot to warm sub moist lowlands
SM2	Tepid to cool sub moist mid highlands
SM3	Cold to very cold sub moist sub afro-alpine to afro-alpine
M1	Hot to warm moist lowlands
M2	Tepid to cool moist mid highlands
M3	Cold to very cold moist sub afro-alpine to afro-alpine
SH1	Hot to warm sub humid lowlands
SH2	Tepid to cool sub humid mid highlands
SH3	Cold to very cold sub humid sub afro-alpine to afro-alpine
H1	Hot to warm humid lowlands
H2	Tepid to cool humid mid highlands
H3	Cold to very cold humid sub afro-alpine to afro-alpine
Ph1	Hot to warm per-humid lowlands
Ph2	Tepid to cool per-humid mid highlands
Source: MoARD (2000).	

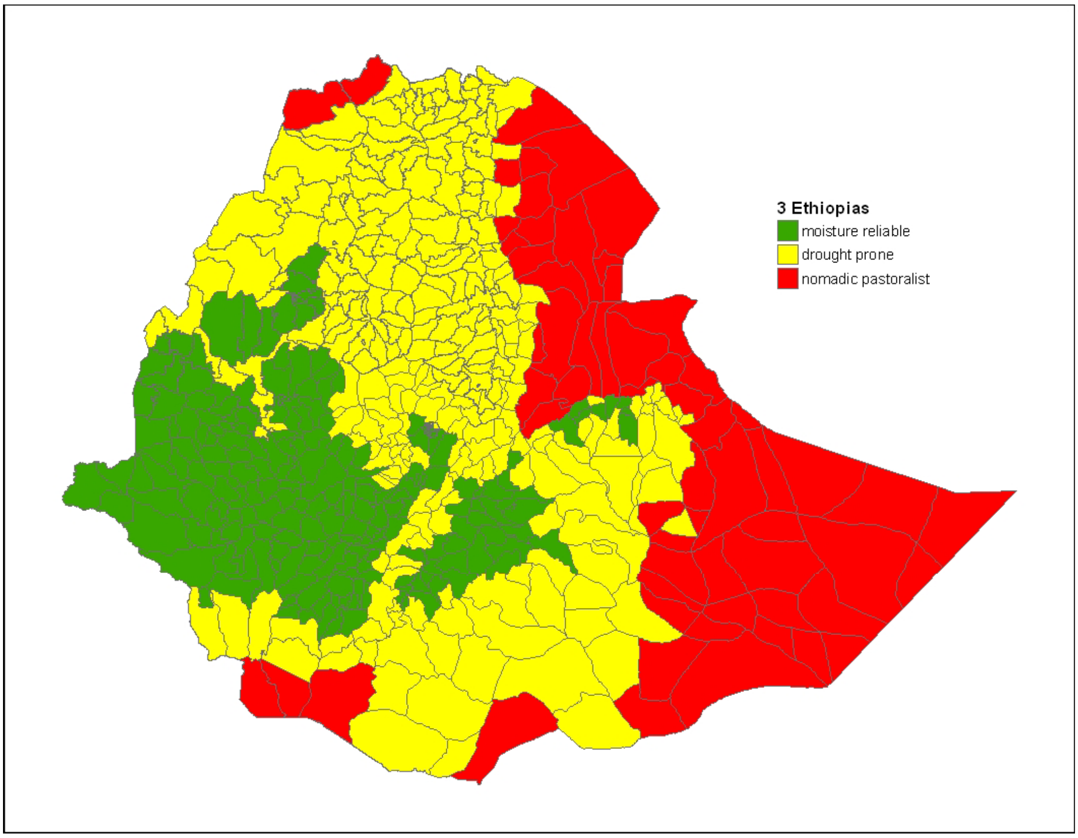
67. Thus, the “three Ethiopias” consists of the humid moisture reliable West and South Western Ethiopia; the moist Drought Prone areas with inadequate and unreliable rainfall of Eastern Highlands, Central and North Eastern Ethiopia; and finally the arid Pastoral Lowlands consisting of the Eastern shelf of the country, much of the Afar and Somali regions. Other Pastoral areas also include the Southern tip of the country, mainly in Borena (Moyale), Kuraz, Hammer Bena, and Teltelie.

68. Ethiopia’s diversity is a key source of both potential and vulnerability. Its diverse topographic and climatic features, agro-ecological zones, and degrees of access to land and reliable water sources reflect its different levels of potential and limitations. However, Ethiopia is prone to extreme weather events. Rainfall in Ethiopia is highly erratic, and most rain falls intensively, often as convective storms, with very high rainfall intensity and extreme spatial and temporal variability. Since the early 1980s, the country has suffered

seven major droughts, five of which led to famines in addition to dozens of local droughts.[15] Survey data show that between 1999 and 2004 more than half of all households in the country experienced at least one major drought shock.[16] Major floods occurred in different parts of the country in 1988, 1993, 1994, 1995, 1996 and 2006.[17]

69. Ethiopia is endowed with a substantial amount of water resources. The surface water resource potential is impressive, but little developed and unevenly distributed across regions.[18] The country possesses twelve major river basins including the Nile basin and the Rift Valley, and is known as the "water tower" of North-East Africa, yet the country has one of the lowest reservoir storage capacities in the world; 50 cubic meters per person compared with, e.g., 4,700 in Australia.[19]

Figure 1: Main Climatic Zones of Ethiopia



Source: MoARD (2000).

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[15] Diao and Pratt (2007).

[16] UNDP (2007)

[17] ICPAC (2007)

[18] FAO (2005); World Bank (2006).

[19] UNDP (2007). For an in-depth assessment of Ethiopia's water resources see World Bank (2006).

4. PROJECTIONS OF LONG-RUN CLIMATE CHANGE FOR EAST AFRICA AND ETHIOPIA

4.1 Temperature and Precipitation Projections

70. Table 9 summarizes long-run temperature and rainfall projections for East Africa in the IPCC Fourth Assessment Report. The projections are based on simulations of 21 global atmosphere-ocean general circulation models (GCMs) under the IPCC A1B scenario.[20]

Table 9: Projected Mean Increase in Temperature and Precipitation in East Africa for the Period 2080-99 in Relation to the Period 1980-99

Season	**Temperature Response (^{o}C)**					**Precipitation Response (%)**				
	Min	25%	Median	75%	Max	Min	25%	Median	75%	Max
DJF	2.0	2.6	**3.1**	3.4	4.2	-3	6	**13**	16	33
MAM	1.7	2.7	**3.2**	3.5	4.5	-9	2	**6**	9	20
JJA	1.6	2.7	**3.4**	3.6	4.7	-18	-2	**4**	7	16
SON	1.9	2.6	**3.1**	3.6	4.3	-10	3	**7**	13	38
Annual	1.8	2.5	**3.2**	3.4	4.3	-3	2	**7**	11	25

Source: Christensen et al (2007), Tab 11.1.

Notes: The figures show averages of temperature and precipitation projections from a set of 21 global models in the multi-model data set (MMD) for the A1B scenario. The mean temperature and precipitation responses are first averaged for each model over all available realizations of the 1980 to 1999 period from the 20th Century Climate in Coupled Models (20C3M) simulations and the 2080 to 2099 period of A1B. Computing the difference between these two periods, the table shows the minimum, maximum, median (50%), and 25 and 75% quartile values among the 21 models for temperature (°C) and precipitation (%) change. Seasons: DJF: December, January, February etc. East Africa is defined as a grid cell extending from 12S 22E to 18N 52E.

71. The IPCC Report notes that the "Models have significant systematic errors in and around Africa. ... Vegetation feedbacks and feedbacks from dust aerosol production are not included in the global models. Possible future land surface modification is also not taken into account in the projections. The extent to which current regional models can successfully downscale precipitation over Africa is unclear, and limitations of empirical downscaling results for Africa are not fully understood. There is insufficient information on which to assess possible changes in the spatial distribution and frequency of tropical cyclones affecting Africa" (Christensen et al, 2007, p.866).

72. Despite these qualifications, the prediction of an increase in annual mean rainfall in East Africa is considered as *likely* in the IPCC Report and is a robust result across the ensemble of models, with 18 of 21 models projecting an increase in the core of this region, east of the Great Lakes (ibid. p.869). This prediction is also consistent with earlier results for the IPCC Third Assessment Report (see Hulme et al, 2001 and Ruosteenoja et al, 2003). However, Ethiopia is not part of this core region and a closer look at country-specific projections reveals a less clear-cut picture with respect to precipitation.

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[20] See Appendix B at the end of this paper for a characterisation of this and the other socio-economic SRES (Special Report on Emission Scenarios) scenarios referred to in this section. In terms of the projected CO_2 concentration levels, scenario A1B can be considered as an intermediate scenario.

73. Table 10 reports projections for Ethiopia from a subset of five higher-resolution GCMs for two alternative SRES scenarios. While three models predict notable long-run increases in average monthly precipitation, one model generates virtually no change and one further model simulates a substantial decline. While the mean of the precipitation change predictions across this set of models is positive, the corresponding annualized mean precipitation change over a different, yet partially overlapping, set of six GCMs in Table 11 has a negative sign.

Table 10: Predicted Climate Change for Ethiopia from High-Resolution GCMs

	CGCM2		**CSIRO2**		**ECHam4**		**HadCM3**		**PCM**	
	2050	**2100**	**2050**	**2100**	**2050**	**2100**	**2050**	**2100**	**2050**	**2100**
Precipitation change in %										
A2 and B2	-13	-28	0	+1	+12	+32	+9	+22	+5	+12
Temperature change in ^{o}C										
A2	3.3	8.0	3.6	8.7	3.2	8.0	3.8	9.4	2.3	5.5
B2	2.9	5.1	3.7	6.6	3.1	5.6	3.8	6.7	2.3	4.0

Note: Adapted from Strzepek and McCluskey (2007: Tables 8 and 9). Figures are changes from a 1961-90 base for SRES A2 and B2. For comparisons with Table 9, the differences in time periods and underlying scenario assumptions need to be borne in mind. The assumed CO_2 concentration level in 2100 is 711 ppm for A1B, 857 ppm for A2 and 615 ppm for B2.

74. For the prediction of agricultural productivity impacts of climate change, a seasonal breakdown of these long-period averages is required, given that the reported figures may mask significant seasonal variability in predicted climate change impacts. As Table 11 shows, this is indeed the case for the predicted impacts of global warming on precipitation in Ethiopia from high-resolution GCMs. It should be noted that the predicted decline in June to September rainfall in Table 11 appears to be consistent with already observable trends for parts of Ethiopia. Cheung, Senay and Singh (2008) find a significant decline in June to September rainfall (Kiremt) for the Baro-Akobo, Omo-Ghibe, Rift Valley, and Southern Blue Nile watersheds located in the south-western and central parts of Ethiopia over the period 1960-2002, yet no significant trend in Ethiopian total annual rainfall. Similarly, Seleshi and Zanke (2004) report a significant decline of annual and June-September rainfall for stations located in the South-West (Gore), South (Negele) and East (Jijiga) since about 1982. A recent study by Funk et al (2008) reports a declining trend for growing-season precipitation in crop-growing areas of Ethiopia and other Eastern African countries over the period 1979-2005 and links this observation to warming of the Indian Ocean through mechanisms not adequately captured by current GCMs. Correspondingly, this study concludes that “recent climate change impact assessments, based on optimistic precipitation simulations over Eastern Africa, may underestimate yield reductions”.

Table 11: GCM Predictions of Climate Change in Ethiopia by Month and Season

Average Monthly and Seasonal Temperature (Degree Celsius)								
	1961-90	**2070-99**	**Change**		**1961-90**	**2070-99**	**Change**	**%**
Feb	22.62	26.29	3.67	**Spring**	23.66	27.41	3.75	15.9
Mar	23.93	27.65	3.72					
Apr	24.42	28.29	3.87					
May	24.45	28.31	3.86	**Summer**	23.98	28.02	4.04	16.8
Jun	24.21	28.40	4.19					
Jul	23.28	27.34	4.06					
Aug	23.04	26.93	3.89	**Fall**	23.11	27.04	3.93	17.0
Sep	23.38	27.31	3.93					
Oct	22.92	26.88	3.96					
Nov	21.95	25.58	3.63	**Winter**	21.58	25.20	3.62	16.8
Dec	21.28	24.85	3.57					
Jan	21.52	25.18	3.66					
Average Monthly Precipitation by Month and Season (mm per month)								
	1961-90	**2070-99**	**Change**		**1961-90**	**2070-99**	**Change**	**%**
Feb	17.08	24.64	7.56	**Spring**	44.99	47.84	2.85	6.3
Mar	37.20	39.68	2.48					
Apr	80.70	79.20	-1.50					
May	89.28	72.85	-16.43	**Summer**	93.58	74.46	-19.13	-20.4
Jun	68.40	41.40	-27.00					
Jul	123.07	109.12	-13.95					
Aug	127.10	117.18	-9.92	**Fall**	92.98	87.77	-5.21	-5.6
Sep	85.50	70.80	-14.70					
Oct	66.34	75.33	8.99					
Nov	31.50	51.60	20.10	**Winter**	17.63	30.22	12.59	71.4
Dec	10.54	18.91	8.37					
Jan	10.85	20.15	9.30					

Note: Own calculations based on Cline (2007: Tables H1-H4. The predictions for 2070-99 are averages of the results from the six GCMs (ECHAM4/OPYC3, HadCM3, CSIRO-Mk2, CGCM2, GFDL-R30 and CCSR/NIES) available from the IPCC Data Distribution Center for the SRES A2 scenario. The delineation of seasons follows Kurukulasuriya et al (2006).

75. Given the wide range of precipitation forecasts across the different GCMs, it appears advisable to discriminate between the conflicting models according to their ability to track observable climate conditions for the region. However, a comparative assessment of GCMs according to this criterion is beyond the scope of this pilot study[21], and would also seem premature at this stage, given the aim to work with a regionally disaggregated model that distinguishes the main climatic zones of Ethiopia for the detailed Phase 2 country study.

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[21] For an earlier limited comparative assessment of 11 GCMs along these lines see AchutoRao et al (2004). According to Thornton et al (2006), McHugh (2005) identifies five out of 19 GCMs "that represent rainfall patterns in East Africa relatively well", among them HadCM3 and ECHam4. Thornton et al (2006) furthermore note that "there seems to have been relatively little validation work carried out on GCMs for African conditions ..., and this is an area that would benefit from further work".

76. For given CO_2 forcing levels, there is less variation in the predicted temperature changes across the various GCMs. Linear extrapolation of the reported figures yields a temperature rise on the order of 0.9 to 1.5 ^{o}C over the 2001-2030 simulation horizon of the present study.

4.2 Changes in Climate Variability and Frequency of Weather Extremes

77. The IPCC 2007 Report notes that research on changes in extremes specific to Africa, in either models or observations, is limited. A general increase in the intensity of high-rainfall events is expected in Africa, as in other regions (Christensen et al, 2007, p.871).

78. Fowler and Hennessy (1995) review physical and empirical arguments which suggest that global warming may result in a more intense hydrological cycle, with an associated increase in the frequency and/or magnitude of heavy precipitation. The analysis of output from three GCMs in this study indicates the possibility of substantial increases in the frequency and magnitude of extreme daily precipitation, with amplification of the effect as the simulation period increases. However, the analysis does not cover African regions.

79. At the same time, some models also project more frequent or severe drought periods over land areas in Africa. It is widely agreed that an important source of inter-annual climate variability in the tropics and beyond is the El Niño Southern Oscillation (ENSO) phenomenon (e.g. Thornton et al, 2006). In Ethiopia ENSO events appear to be related to the occurrence of droughts. However, it is not clear whether ENSO events will change character in response to global warming, though recent simulations with the ECHAM4 GCM cited by IPCC-TGICA (2007) indicate an increase in the frequency of ENSO events.

80. There is little agreement between GCMs about possible changes in the frequency and intensity of mid latitude storms and tropical typhoons under climatic warming.

81. In the published GCM-based literature reviewed for this report, the potential increase in climate variability is largely discussed in qualitative terms as opposed to quantitative probabilistic terms, and we have been so far unable to track down studies that try to predict increased variances in climatic variables or increased frequencies of extreme weather events quantitatively for East Africa in general or Ethiopia in particular. There appears to be a consensus that the current state of the art in GC modeling does not allow predictions of that kind with any degree of confidence. As the IPCC Fourth Assessment Report puts it:

> “(U)nderstanding how possible climate regime changes (e.g., in El Niño-Southern Oscillation (ENSO) events) may influence future climate variability is critical in Africa and requires further research” (Boko et al, 2007, p.436).

5. CLIMATE CHANGE IMPACTS ON AGRICULTURAL PRODUCTIVITY IN ETHIOPIA: REVIEW OF EXISTING LITERATURE

82. Given the strong dependence of Ethiopia's economy on rain-fed agriculture, the dominant channel through which medium-and long-run changes in the means and variances of climatic variables affect economic performance will be the link from climate to agricultural yields. This section reviews existing studies of potential climate change impacts on agricultural productivity in the region.

5.1 Studies Based on the Ricardian Approach

83. The Ricardian method for estimating the impacts of climate change on agriculture is a cross-section regression of land values or net revenue against climate and other exogenous characteristics (Mendelsohn et al, 1994). An advantage of the Ricardian model is its ability to incorporate adaptation to climate change in implicit form. The model is based on the assumption of profit-maximizing behavior and this implies that farmers will adapt to climate change by changing the output mix, planting and harvesting dates, and other crop management practices. The farmers' response entails costs and thus affects net revenue. Accordingly, the Ricardian approach takes adaptation into account by measuring economic damages and adaption as reductions in net revenue or land value induced by climatic factors (Deressa, 2006).

84. For present purposes, the most relevant study of this type is Kurukulasuriya et al (2006) which uses survey data for around 9000 farms across 11 African countries including Ethiopia[22] and runs separate regressions for drylands, irrigated land and livestock. The study takes account of non-linearities in the relationship between agricultural production and climate by including quadratic forms for precipitation and temperature by season. Obviously, the cross-sectional approach is unable to account for potential fertilization effects due to higher global CO_2 concentration levels.

85. Table 12 shows the estimated coefficients for temperature and precipitation by season for drylands as well as the resulting simulated changes in net revenue per ha, when the GCM-based predicted seasonal changes in rainfall and temperature from Table 11 above are fed into the model. The transformation of the net revenue effect into an output effect for a given level of inputs at the bottom of the table is based on a ratio of net revenue to gross output value on the order of 0.6 derived from the 2001/02 SAM for Ethiopia. In line with the time horizon for the dynamic CGE simulation analysis, the resulting crop agriculture productivity effect of around -7.4% represents by construction the total effect over the period 2001 to 2030 due to changes in the seasonal monthly means of precipitation and temperature as derived from Table 11 via linear interpolation.

86. The only Ricardian approach study specifically for Ethiopia we are aware of is Deressa (2006) under the Global Environment Facility—World Bank Project *Regional Climate, Water and Agriculture: Impacts on and Adaptation of Agro-ecological Systems in Africa*. The study is based on data elicited from interviews with 1000 farmers across 11 agro-ecological zones. On the one hand, the reported regression analysis suggests that marginal changes in seasonal climate variables have quite dramatic—and in many cases implausibly

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[22] Cline's (2007) estimates of agricultural climate change impacts by country are partially based on this study.

large—yield effects. On the other hand, when the predicted large changes in temperature and rainfall are fed into the Deressa model, the reported yield effects are miniscule, and so we are unable to arrive at a consistent interpretation of the reported results. Moreover, some of the signs of the marginal effects appear to contradict received wisdom. For these reasons, the results of this study are not reported here.

87. With respect to potential impacts of climate change on livestock yields, Seo and Mendelsohn (2007) distinguish direct and indirect effects. Direct effects from temperature, humidity and other climate factors influence animal performance in terms of growth, milk production, wool production and reproduction. Indirect effects include climatic influences on the quantity and quality of feed such as pasture, forage, grain and the incidence of livestock diseases and parasites. According to the same authors, the effect of increased CO_2 on the amount of grassland seems to be neutral or positive, if potential CO_2 fertilization effects are taken into account. While a decrease in mean annual precipitation in Africa is expected to have a negative impact on grassland, a simultaneous increase in water use efficiency resulting from CO_2 doubling could offset this negative effect. African livestock productivity has been severely affected by vector-borne livestock diseases known to be climate sensitive.

Table 12: Agricultural Net Revenue Effects of Climate Change for Dryland Crops - Ricardian Approach

	Temperature		**2085**	**2030**
	linear	**squared**	**Partial effect in $**	
Spring	-28.00	-1.00	-296.76	-85.59
Summer	125.00	-1.40	210.73	65.15
Fall	-58.00	0.40	-148.97	-44.73
Winter	-68.00	2.50	177.26	47.87
	Sum Temperature		-57.74	-17.29
	Precipitation		**2085**	**2030**
	linear	**squared**	**Partial effect in $**	
Spring	4.70***	-0.01**	10.74	3.55
Summer	3.60***	-0.01***	-36.72	-11.34
Fall	-2.10**	0.01***	1.52	0.45
Winter	-4.60***	0.03***	-39.84	-14.10
	Sum Precipitation		-64.30	-21.44
		Total in $	-122.04	-38.73
		%	-38.30	-12.10
		Output effect %		-7.38
		p.a		-0.26

Source: Estimated coefficients in column 2 and 3 from Kurukulasuriya et al (2006: Table 1).

Notes: ***significant at 1 percent level, **significant at 5 percent level. Columns 4 and 5: Own calculations as explained in text. The figures in the last column are based on changes in climate variables relative to a 2001 base.

Dependent variable is net farm revenue per hectare in 2005 US dollars. Additional control variables include water flow, elevation, household size, household electricity, and 22 soil types. $R^2 = 0.16$. Average net revenue: dryland, $319 per hectare; irrigated, $1,261 per hectare. Seasons for the Southern Hemisphere are defined as: winter (May–July), spring (August–October), summer (November–January), and fall (February–April). The months are the same but the seasons reversed for the Northern Hemisphere.

88. The combination of the predicted changes in the seasonal means of temperature and rainfall for Ethiopia from Table 11 with the estimated Ricardian livestock revenue model of Kurukulasuriya et al (2006) in Table 13 suggests, perhaps surprisingly, that livestock yields benefit marginally from global warming as positive effects due to higher temperatures dominate adverse impacts due to changes in precipitation patterns. The Table exhibits some remarkable sign reversals due to non-linearities between the seasonal medium-run effects up to 2030 and the long-run effects. For spring and fall temperatures the sign pattern of the estimated coefficients suggests an inverse U-shaped relationship between temperature and livestock revenue. According to the estimates current mean temperatures are sub-optimal during these seasons and the 1.1 ^{o}C rise by 2030 shifts net revenues closer to the optimum, yet the further rise in temperature by 2085 on the order of nearly 4 ^{o}C pushes livestock production beyond the optimum and down the right branch of the inverse U. The opposite kind of sign reversal is suggested for winter temperatures where the model suggests a U-shaped relationship.[23]

89. The suggestion of a slightly positive impact of changes in the seasonal means of rainfall and temperature on livestock production Ethiopia is untypical compared to the results for most other sub-Saharan African countries in the Kurukulasuriya et al (2006) sample, and needs to be interpreted with a generous dose of caution, yet the result is consistent with the authors' own calculations of country-specific effects (ibid., Fig.4). In particular, it should be borne in mind that the Ricardian approach is based on the assumption that the data-generating process underlying the observation is itself not affected by global warming and thus does not capture the potential impacts of increased future climate variability.

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[23] Both the linear and the quadratic coefficients for mean winter temperature are highly significant, yet it is not immediate obvious to see why a continuously rising winter temperature should (ceteris paribus) initially reduce but then from some point onwards boost livestock revenue as temperatures rise further.

Table 13: Agricultural Net Revenue Effects of Climate Change for Livestock Crops - Ricardian Approach

	Temperature		**2085**	**2030**
	linear	**squared**	**Partial effect in $**	
Spring	6772.00**	-136.00**	-649.58	64.14
Summer	-2904.00**	58.00**	451.33	6.94
Fall	4679.00**	-95.90**	-513.23	45.99
Winter	-8643.00**	191.00**	1061.58	-21.02
	Sum Temperature		350.09	96.05
	Precipitation effects		**2085**	**2030**
	linear	**squared**	**Partial effect in $**	
Spring	35.20	-0.32**	15.64	5.68
Summer	34.90**	-0.17**	-121.13	-27.13
Fall	-23.50**	0.11**	18.85	5.60
Winter	-3.70	-0.18	-155.02	-45.21
	Sum Precipitation		-241.67	-61.06
		Total in $	108.42	35.00
		%	6.90	2.20
		Output effect %		1.34
		p.a		0.05

Source: Estimated coefficients in column 2 and 3 from Kurukulasuriya et al (2006: Table 1).

Notes: **Significant at 5 percent level. Columns 4 and 5: Own calculations as explained in text. The figures in the last column are based on changes in climate variables relative to a 2001 base.

Dependent variable is net revenue per farm in 2005 US dollars. Additional control variables include water flow, elevation, household size, household electricity, and 22 soil types. $R^2 = 0.22$. Average net revenue per farm: $ 1566. Seasons for the Southern Hemisphere are defined as: winter (May–July), spring (August–October), summer (November–January), and fall (February–April). The months are the same but the seasons reversed for the Northern Hemisphere.

5.2 Studies Using Process Based Crop Simulation Models

90. An alternative approach to the prediction of long run climate change impacts on agricultural productivity links the temperature and precipitation estimates from GCMs to process-based crop models that capture the main physiological processes responsible for plant growth in a stylized form and enable the prediction of yield as a function of climate variables, soil type, moisture and crop management practices. The yield effects for four major crop types in an African sub-region including Ethiopia in Table 14 are drawn from Rosenzweig and Iglesias (2006) and provide refined updates of an earlier study by Rosenzweig, Parry, Fischer and Frohberg (1993). The crop models used in this study have been validated over a wide range of environments. The estimates assume the implementation of adaptation measures that imply small additional cost to farmers including shifts in planting dates, additional irrigation to crops already under irrigation and changes in crop varieties to currently available varieties more adapted to the altered climate. Correspondingly, the estimates are not subject to the strong form of the "dumb farmer" critique frequently raised against the crop simulation approach. The estimates make no allowance for autonomous (i.e. CO_2-independent) technical progress.

Table 14: Crop Model Predictions - Rosenzweig and Iglesias (2006)

Yield changes in % (base 1980)	**All**	**Soy beans**	**Coarse grains**	**Rice***	**Wheat**
No CO_2 Fertilization					
2020 (475 ppm)	-9	-10	-10	-8	-8
2050 (574 ppm)	-17	-18	-18	-16	-16
2080 (712 ppm)	-28	-28	-28	-28	-28
With CO_2 Fertilization					
2020 (475 ppm)	-4	-2	-6	-4	-2
2050 (574 ppm)	-6	-1	-14	-5	-4
2080 (712 ppm)	-13	-5	-22	-12	-11

*Not produced in Ethiopia.

Estimates are for "Africa low-income calorie exporters" including Ethiopia, Sudan, Mozambique, Uganda, Benin, Gambia and Togo. Coarse grains are cereal grains other than wheat and rice (maize, barley, sorghum, oats). For the estimates reported here, the HadCM3 GCM (UK Met Office) is forced with the atmospheric CO_2 concentration levels reported in parentheses. The resulting regional temperature and rainfall predictions are fed into regionally calibrated version of the CERES-Wheat, CERES-Maize, CERES-Rice and SOYGRO crop simulation models with and without CO_2 enrichment effects under the assumption of low-cost adaptation of crop management practices as described in the main text. For further methodological details see Rosenzweig and Iglesias (2006).

91. Table 15 reports results based on the same methodology for the Stern Review spanning the whole range of SRES emission scenario. In both tables, the sensitivity to the assumed presence or absence of positive CO_2 fertilization effects is clearly visible. The issue of CO_2 fertilization is subject to notorious debate. Recent free-air carbon enrichment (FACE) studies have called into question the results of earlier closed-laboratory experiments that suggest the presence of strong positive productivity effects for major crops due to higher CO_2 concentration levels (Long et al, 2006). Yet the validity of FACE results has likewise been questioned (see Tubiello et al, 2007), and the debate appears to be unresolved at present.[24]

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[24] See Cline (2007) for further discussion.

Table 15: Crop Model Predictions – Warren et al (2006) for Stern Review

% changes in yields of maize and wheat in Southern and East Africa relative to 1990 base

	2020	2050	2080
	Maize with CO_2 fertilization		
South and East Africa	-2.5 to -4.8	-6.2 to -8.2	-11.7 to -20.8
World	-2.5 to -4.2	-5.0 to -6.1	-6.3 to -8.9
	Maize without CO_2 fertilization		
South and East Africa	-3.5 to -4.7	-7.6 to -15.2	-13.7 to -28.8
World	-3.5 to -4.2	-6.3 to -10.3	-9.9 to -16.9
	Wheat with CO_2 fertilization		
South and East Africa	+1.4 to -0.6	+1.6 to -2.8	-3.2 to -15.3
World	+1.2 to -0.6	+2.5 to -0.6	+2.7 to -3.5
	Wheat without CO_2 fertilization		
South and East Africa	-2.6 to –3.6	-6.8 to -13.8	-11.2 to -33.3
World	-2.8 to -4.1	-5.7 to -9.8	-8.1 to -21.5

Source: Warren et al (2006: Tables A5-A7) based on Parry et al (2004). Same methodology as Rosenzweig / Iglesias (2006), i.e. linkage of HadCM3 with CERES crop models under low-cost adaptation. In contrast to the results in Table 13, the reported results span SRES scenarios A1F, A2, B1, B2.

92. When the figures in Tables 14 and 15 without CO_2 fertilization are expressed as changes up to 2030 from a 2001 base via interpolation, the orders of magnitude—roughly -3.5 to -7.3% for maize/coarse grains and -2.6 to -5.8% for wheat—are remarkably close to the -7.4% figure for crop agriculture derived from the Ricardian approach in Table 12.

93. A study by Jones and Thornton (2003) uses complex high-resolution methods in combination with the CERES-maize crop model to estimate climate change impacts on maize yields in Africa and Latin America up to 2055 at a very fine level of regional disaggregation. The study suggests for Ethiopia, that country-level estimates may hide enormous regional intra-country variation:

> "One such area is in the Ethiopian highlands surrounding Addis Ababa ..., where substantial localized yield increases are predicted, sometimes up to 100%, although many of the pixels showing yield increases are adjacent to pixels where yields are predicted to decline, sometimes drastically." (p.55)

94. As noted by Challinor et al (2007), crop modeling has focused virtually exclusively on the world's major food crops. A consequence of this is that the simulation of some crops and local crop varieties common to African farming systems, such as sorghum, teff, millet, etc is underdeveloped or non-existent. Correspondingly, there is at present no solid scientific basis for a fine-tuned crop-specific assignment of productivity shocks for the various crop activities identified in the dynamic general equilibrium model employed in section 8. As detailed in section 7.2, the approach pursued in the present study addresses this problem by drawing on historical observations of the co-variation in crop productivity for Ethiopia across the range of crops identified in the model.

5.3 Impacts of Climate Variability and Extreme Weather Events

95. As noted in section 4, a range of GCMs predict not only changes in the means of rainfall and temperature, but also an increased inter- and intra-annual variability around the

means entailing a potential increase in the likelihood of crop-damaging extreme weather events including floods, droughts, heat waves. In the presence of non-linearities and threshold effects in the relationship between climate variables and agricultural yields, the crop simulation estimates of productivity effects as well as the estimates derived from Ricardian regressions, may significantly underestimate the impacts.

96. It was pointed out in section 3 that both droughts and floods are already endemic in the country. Droughts destroy farmlands, and pastures, contribute to land degradation, cause crops to fail and livestock to perish. During the 1984–5 drought, GDP declined by around 10 percent and during the recent 2002-3 drought by over 3 percent. Drought can also severely affect hydropower generation, Ethiopia's main source of electricity. Flooding in turn causes significant damage to settlements and infrastructure, and the water-logging of productive land undermines agriculture by delaying planting, reducing yields, and compromising the quality of crops, especially if the rains occur around harvest time (World Bank, 2006).

97. Warren et al (2006) notes that the HadCM3 GCM predicts a dramatic increase in natural climate variability, to the extent that global and regional temperatures will fluctuate on an annual basis over a range equal to more than half the increase in temperature predicted over the next 80 years. Challinor *et al* (2006) consider extremes of temperature, and point out how only a few days of high temperatures near flowering in wheat, groundnut and soybean can drastically reduce yield.

98. As Semenov and Porter (1995) point out in one of the first studies that take climate variability into account, non-linearity of crop responses entails the necessity to preserve the variability of weather sequences to estimate the effect of climate on agricultural production and to assess agricultural risk. In their study, the authors couple a crop simulation model for wheat with a stochastic weather generator. This approach allows changes not only in mean values but also in the variance or type of distribution for climate variables. Their results for Southern France indicate that changes in climatic variability can have a more profound effect on yield and its associated risk than changes in mean climate. Porter and Semonov (2005) cite simulation results for wheat, in which a doubling of the standard deviation of temperature is estimated to generate the same decrease in yield as a 4^{o}C increase in mean temperature.

99. The incorporation of climate variability in the presence of non-linearities and threshold effects along these lines is a highly complex problem and currently an active area of research. The only study of this type for Ethiopia is exploratory work by Block, Strzepek, Rosegrant and Diao (2006) which focuses on hydrological variability in the presence of a flooding threshold.

5.4 Effects on Cropland Area and Soil Erosion

100. Lotsch (2007) analyzes potential effects of climate change on cropping pattern using a logistic regression model to predict cropland use in combination with GCM projections. The analysis suggests that cropland area in Africa is likely to decrease significantly in response to transient changes in climate. The continent is expected to have lost on average 4.1% of its cropland by 2039, and 18.4% is likely to have disappeared by the end of the century. In some regions of Africa the losses in cropland area are likely to occur at a much faster rate, with northern and eastern Africa losing up to 15% of their current cropland area within the next 30 years or so. However, closer inspection of the geographical maps presented in this study shows that the negative effects for East Africa are concentrated in areas of South East Africa,

while the predicted cropland changes for Ethiopia appear to be generally negligible or slightly positive.

101. However 79 percent of Ethiopia’s land has a slope in excess of 16 percent, and at least one-third of this area has a slope of 30 percent or more. Torrential rains result in a heavy flush of water that washes away the soil. Crops that have not yet adequately rooted during the early part of the rainy season may also be washed away along with the soil. Studies cited in World Bank (2006) indicate that in many areas erosion exceeds soil formation. Soil erosion due to heavy rain is exacerbated by severe deforestation and traditional agricultural practices involving the cultivation of steep slopes without protective measures. The loss of forest cover, in turn, is generally associated with greater hydrological variability. These soil erosion problems are likely to be acerbated by a rise in the frequency of extreme weather events.

6. OTHER CLIMATE CHANGE IMPACTS

6.1 Health

102. Tol (2002) identifies six broad channels through which climate change affects human health: (i) morbidity and mortality is influenced by temperature extremes; (ii) the vectors of infectious diseases are affected by climate; (iii) the proliferation of non-vector-borne infectious diseases depends inter alia on weather conditions; (iv) air quality affects health and is influenced by weather; (v) floods and storms injure and kill people; (vi) human health may be influenced indirectly by climate change for instance via influences on food supply and water resources.

103. A detailed World Health Organization (WHO) study (McMichael et al, 2004) estimates an annual loss of 36 thousand lives across East Africa already in 2000 due to anthropogenic climate change relative to a 1990 baseline as shown in Table 16. The Table also reports health risk for 2030 relative to 1990 predicted by the same study for a range of emission scenarios.[25]

Table 16: Morbidity and Mortality Impacts of Climate Change in East Africa

	Mortality 2000 ***in 1000 deaths***	**Disease 2000** ***in 1000 DALY***	**Relative Risk 2000**	**Relative Risk 2030**
Cardiovascular diseases	1	-	1.00-1.003	1.00-1.01
Diarrhea	8	260	1.00-1.05	0.99-1.16
Malaria	18	682	1.00-1.08	1.00-1.28
Inland floods	0	3	1.00-1.54	1.00-3.18
Malnutrition	9	323	1.00-1.02	1.00-1.08
All	36	1268		
Per million	109.4	3839.6		

Source: McMichael et al (2004). All figures compared to 1990 baseline climate. DALY: Disability-adjusted life year reduction (equivalent years of 'healthy' life lost in states of less than full health, broadly termed disability. One DALY represents the loss of one year of equivalent full health). Figures in the last two columns show upper and lower bounds of relative probabilities across three alternative emission scenarios.

104. The figures suggest that for Ethiopia the most pertinent direct health risk attributable to climate change is a potential increase in the incidence of malaria via Tol’s channel (ii). According to WHO data, 68% of the Ethiopian population already live in areas at risk of malaria. Malaria transmission in Ethiopia is unstable and characterized by frequent and often large-scale epidemics. In 2003, large-scale malaria epidemics resulted in 2 million clinical and confirmed cases and 3000 deaths.

105. The IPCC Fourth Assessment Report cites predictions that previously malaria-free highland areas in Ethiopia could experience modest incursions of malaria by the 2050s, with

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[25] See Patz et al (2005) for a brief critical review of this study and related studies.

conditions for transmission becoming highly suitable by the 2080s.[26] A rising incidence of malaria has already been observed in high-altitude sites of Kenya, Uganda, Rwanda and Burundi, yet the attribution of these observations to global warming remains controversial, since the evidence on warming trends in these sites is not clear-cut and other confounding explanatory factors including changes in drug resistance, vector and disease control programs and land use appear to play a significant role.[27] As pointed out in the Human Development Report 2007/2008 (UNDP 2007), the risks of malaria and other infectious diseases can also interact with increased flooding risks in the region:

> "Changing weather patterns are already producing new disease profiles in many regions. In eastern Africa, flooding in 2007 created new breeding sites for disease vectors such as mosquitoes, triggering epidemics of Rift Valley Fever and increasing levels of malaria. In Ethiopia, an epidemic of cholera following the extreme floods in 2006 led to widespread loss of life and illness" (UNDP, 2007).

106. However, yet again the attribution of such observations is not a resolved issue and in the case of Ethiopia with its high natural climate variability and long history of extreme weather events, the line between events genuinely triggered by anthropogenic global warming and other natural weather extremes is particularly difficult to draw.

107. To the extent that an uncontrolled spread of malaria will induce migration flows to higher altitudes with further adverse consequences for land degradation in these regions, increased malaria risks will potentially also interact with land productivity.

108. A study by Amarcher et al (2004) reports an increase in the incidence of malaria as a side effect of microdam constructions that provide new breeding habitats for mosquitoes in the Tigray region of Ethiopia. This finding suggests that climate change adaptation measures in the form of water resource development investments may as well interact adversely with health risks.

109. The dynamic CGE modeling approach outlined in the following section can in principle capture morbidity and mortality effects as well as the effects of preventive and reactive adaptation measures through linkages to the population growth and labor productivity parameters of the model.[28] However, due to the present lack of country-specific quantitative projections of climate-change-induced health effects, the illustrative simulations in section 8 do not attempt to incorporate such impacts. A rough back-of-the-envelope calculation based on the annual mortality and DALY estimates per million of inhabitants and the changes in relative risks in Table 16 would seem to suggest, that the incorporation of health impacts on aggregate labour supply and productivity up to 2030 would not materially affect the simulation results.[29] In view of the temperature projections for Ethiopia beyond

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[26] Boko et al (2007). See also Rogers and Randolph (2000) and Van Lieshout et al (2004). For an assessment of the economic costs of malaria see Sachs and Malaney (2003).

[27] See in particular Hay et al (2002) and Pascual et al (2006).

[28] For empirical studies of health-productivity linkages for Ethiopia see Croppenstedt and Muller (2000), Amarcher et al (2004), Ulimwengu (2008).

[29] This statement should not be misinterpreted to suggest that we consider the additional human suffering inflicted by climate-change-induced health effects as negligible, or that further investments in malaria control and prevention programs are ill-advised. The estimates of a high *overall* economic burden of malaria by Sachs and Malaney (2003) indeed suggest the opposite. However, in the present context a clear conceptual distinction between the *total* and the *additional* economic burden of malaria triggered by global warming is required.

2030 reported in section 4, the inclusion of these linkages will become more important if the simulation horizon is to be extended beyond 2030 in the second phase of the project.

6.2 Energy Supply

110. Ethiopia has considerable hydropower potential. 95 percent of national energy consumption is derived from fuel wood, dung, crop residues, and human and animal power while only 5 percent is from electricity, 90 percent of which is generated by hydropower. According to World Bank (2006), only two percent of the country's economically feasible hydroelectric potential has been developed.

111. Power interruption is common in years of severe drought when water shortages disrupt hydroelectric power generation. The 2002–3 drought caused power interruptions that lasted for about four months with a one-day-per-week complete interruption throughout the country (and the author of these lines witnessed several all-day 9:00-21:00h power cuts per week across Addis Ababa during two visits in May 2008).

112. According to estimates cited in World Bank (2006), a one-day interruption results in a loss of 10–15 percent of the GDP for the day. In the absence of preventive adaptation measures, the frequency of these losses will obviously rise with an increase in the frequency of drought spells.

113. However, the inclusion of the impact of precipitation variability on hydropower generation in future policy simulations will have to take into account emerging developments in the interlinkage of Ethiopia's electric grid with Sudan and Djibouti and later with other neighboring countries, as well as the ongoing hydropower investments noted in section 2 above. These developments may allow the country not only to export surplus power when available, but also to import thermally generated power from Sudan when hydropower generation is constrained. Moreover, the additional hydropower generation capacity will reduce the vulnerability of electricity supply to climatic shocks.

6.3. Other Effects

114. In line with the terms of reference for this study, other potential climate change effects discussed in the pertinent literature such as effects on bio-diversity, conflict and tourism are beyond the scope of this report.

7. SIMULATION METHODOLOGY

7.1 The CGE Model Framework

115. The dynamic simulation approach starts from the standard, single-country, computable general equilibrium (CGE) model and extends it for the analysis of climate change impacts and adaptation policies.[30] The standard model is first made (recursive) dynamic, including many time periods, in a manner similar to that of the World Bank's MAMS model.[31] The dynamic CGE model is then adapted to analyze issues of climate change (CC). The resulting CC-CGE model focuses on dynamics, incorporates stochastic elements, and is designed for Monte Carlo analysis.[32]

116. For each time period, the model gives a comprehensive, internally consistent account of decisions and related payments involving production, consumption by households and the government, private and public investment, trade, taxation, and transfers between households, government and the rest of the world. Producers are price takers in intermediate input, factor and output markets and maximize intra-temporal profits subject to sectoral CES-Leontief production technologies. Consumer behavior is derived from intra-temporal utility maximizing behavior subject to within-period budget constraints. Utility functions take the Stone-Geary form, yielding a LES demand system specification. Domestic goods and imports are imperfect substitutes in demand. Intra-temporal equilibria are linked intertemporally through growth of the labor force, capital accumulation, and endogenous productivity effects arising from climate shocks.

117. The model is calibrated to a benchmark dataset based on the 2001/02 Social Accounting Matrix for Ethiopia recently constructed at EDRI in collaboration with IDS. The SAM distinguishes 42 production activities including 11 different agricultural activities and 62 commodity groups including 19 agricultural commodities. The aggregated benchmark data set for the present study retains the full agricultural production details of the SAM, but aggregates the manufacturing and service activities. The aggregated SAM to which the model employed in section 8 is calibrated identifies 22 production activities, 24 commodity groups, 2 household groups and 5 primary factors as listed in Appendix Table C.1. The dynamic simulation runs cover a time period of 25-30 years.[33]

7.2 The Treatment of Uncertainty

118. This section describes the approach for treating climate uncertainty and its implications for agricultural production in the Ethiopian context. We accomplish this in two steps. First, we examine historical data on agricultural production by product category

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[30] See Lofgren, Harris, and Robinson (2002) for a description of the standard CGE model that provides the starting point for our model.

[31] See Lofgren and Diaz-Bonilla (2006), which describes the MAMS model and its application to the analysis of the Millennium Development Goals (MDGs).

[32] The CC-CGE model is solved for all time periods simultaneously and can incorporate forward-looking optimizing behaviour by economic agents. In the applications used here, the model is recursive dynamic, with no dynamic optimizing behaviour.

[33] Runs for 30 years were done for sensitivity analysis.

represented in the social accounting matrix in order to determine the historical variation in production trends of each commodity and the tendency for production of various commodities to co-vary. Second, we consider appropriate treatment of future climate outcomes in the context of climate change.

119. To determine historical climate variability, data on indices of agricultural production and land use by commodity for Ethiopia were obtained from FAOStat for the period 1961-2004 (the most recent year for which complete data is available). The following regression was run for each agricultural commodity[34] present in the Ethiopia Social Accounting Matrix (SAM) employed for the analysis described in Section 8:

$$P_{it} = \alpha_i + \beta_i t + \gamma_i t^2 + \delta P_{it-1} + d + \varepsilon_{it} \qquad (1)$$

where subscript i represents crops, t represents time both as a subscript and within the regression (1961=0), t^2 represents time squared, P_{it} represents growth in production in percentage change from period t-1, $P_{it\text{-}1}$ represents lagged growth in production, d represents a dummy variable accounting for political regime change in 1992 and ε_{it} represents an error term. The specification permits production growth to follow a quadratic time trend. The lagged term for percentage growth captures shorter run trends and the tendency for growth trends to revert towards average after a good year or a bad year due to the effect on the base for the percentage change calculation in the following year.

120. For our purposes, the specification assumes that the variability captured in the error term is due primarily to climate outcomes occurring in each crop year. This appears to be a reasonable assumption in the Ethiopian context; however, it bears emphasizing that factors unrelated to climate outcomes could have contributed to production variability as well. For example, political events can reduce production in a given year despite an average climate realization.

121. Results from the regressions typically estimate a negative value for the δ parameter though the parameter is statistically significantly different from zero in only a few cases. Analysis of the residuals squared over time illustrates little tendency for production variance to expand with time on a commodity by commodity basis. However, the index of aggregate agricultural production, as well as the components food, cereals, and livestock, show a significant positive relationship between variability in the growth of production and time. There is no systematic evidence of auto-correlation in either the commodity level or the more aggregate level regressions.

122. For the modeling purposes considered here, the specification is convenient as the error term relates directly to the deviations from trend production due to climate variability. The challenge is to use these error terms to construct a distribution of likely climate outcomes from which one can draw for the simulation of future outcomes in a Monte Carlo analysis. This distribution should preserve the information captured by the moments, including covariances, of the empirical distribution of errors. This is potentially important as climate outcomes unfavorable to commodity A are not necessarily unfavorable to commodity B. The

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[34] See Appendix Table C.1.

correlation may, in fact, be negative where unfavorable outcomes to commodity A are favorable to commodity B.

123. One approach is to assume that the error terms are normally distributed and draw from a normal distribution with appropriate covariance structure. However, the estimated error terms fail tests for normality. As a result, a bootstrap approach was employed. In particular, in the baseline forward-looking stochastic simulations, vectors of error terms were drawn with replacement from the empirical distribution with equal probability for each observed outcome from 1963-2004 (42 possible vectors). A twenty-five or thirty year forward-looking simulation might repeat the realizations observed in particular years. This approach allows one to consider the volatility of agricultural production outcomes under the assumption that underlying climate variability remains the same. In other words, the history of climate realizations is, at first, assumed to be a reasonable guide to future climate realizations.

124. The next step is to consider the implications of climate change for the future distribution of climate outcomes. As discussed in detail earlier in the document, the accumulation of GHGs in the atmosphere implies that underlying climate variability in Ethiopia is likely to change. Globally, climate is, with high confidence, likely to become warmer, wetter, and more volatile (IPCC, 2007). At more refined levels of disaggregation, such as Ethiopia, the magnitude, timing and even direction of climate change is more uncertain, as was illustrated in section 4. The most recent global circulation model results for Africa indicate that Ethiopia will become warmer and have higher probability of intense precipitation. There is much less agreement across models with respect to the probability and duration of drought. Further, beyond the uncertainty associated with the distribution of climate outcomes, there remains uncertainty associated with how different climate outcomes will translate into economic outcomes on the ground (as discussed in sections 5 and 6).

125. For our purposes, it is most useful to consider how the prospect of climate change should influence the way we consider the future for Ethiopia. Two points are particularly relevant. First, with high confidence, the scientific community believes that the global climate is changing due to anthropogenic factors. As Ethiopia is, most certainly, a part of this global system, the parameters underlying climate outcomes in Ethiopia are changing as well. Two implications arise based only on the information that the underlying parameters of the distribution are shifting:

a) The range of possible outcomes (the support of the distribution) may expand.
b) The probability associated with any given set of outcomes may change.

126. In short, because the distribution itself is changing, we are less well informed about the nature of the distribution. From a Bayesian perspective, the uniform distribution across a given support range is the least informative distribution. As climate change leaves us less well informed about the nature of the distribution of climate outcomes for Ethiopia, the distribution of future climate outcomes becomes more like the uniform distribution reflecting our lack of knowledge. The support of that distribution may also expand, for the same reason.

127. Second, as has been discussed, there is some information on the likely implications of global climate change for climate realizations in Ethiopia. The available information points to higher temperatures and greater probability of extreme precipitation events, with greater probability of flooding (ceteris paribus). Higher temperatures are likely to accentuate the impact of consecutive dry days on agricultural output. The probability of increased droughts is, at best, unchanged. Positive outcomes are also possible. If flooding is avoided, increased

frequency of strong precipitation events, such as days with more than 10 mm of precipitation, may result in an increased frequency of strong positive outcomes given the important role of water constraints on total production in Ethiopia.

128. In summary, ignorance about climate change impacts should lead us to project a distribution of climate outcomes that is more uniform (e.g., flattens the center of the distribution and thickens the tails) than the historical data would indicate. This comes about for two reasons. First, our high confidence in the existence of climate change combined with our lack of knowledge about the implications of global climate change for climate outcomes in Ethiopia requires us to consider a more uniform and potentially broader distribution of outcomes. Second, the information that we do have with respect to possible implications of global climate change for Ethiopia points to greater weight at the extremes of the distribution.

129. The critical operational question is exactly how and how much the historical distribution should be modified in order to account for climate change. Unfortunately, this is both unknown and unknowable. We have no choice but to develop a subjective prior distribution of future climate outcomes under the knowledge that climate change renders history an imperfect guide to the future. To address this conundrum, we turn to financial economics where a roughly analogous situation prevails.

130. On a continuous basis, US investors must determine appropriate allocations between low risk allocations, such as government bonds, and high risk allocations such as equities. Long historical experience indicates that investors demand return premiums for investments in equities over government bonds that exceed levels consistent with generally accepted parameters for time preferences and risk aversion combined with historically observed volatility in the growth of output (consumption) by an order of magnitude. Similarly, investors are willing to accept a much lower return on safe assets than theory, historical volatility in output/consumption and reasonable parameters would suggest. Finally, equity prices are far more volatile than standard models would predict. These inconsistencies are labeled the equity premium, risk free rate, and equity volatility puzzles.

131. Recently, Weitzman (2007) offered a unified explanation for all three puzzles. He proves that Bayesian updating of nonergodic systems causes rational agents to significantly thicken the tails of their subjective prior distributions of future outcomes. This "tail thickening" maintains even if the evolution of the underlying system is arbitrarily slow and the volume of data on the underlying systems tends toward infinity. In other words, despite substantial data on economic outcomes in, for example, the United States, the knowledge that the underlying parameters of the economic system are evolving causes investors to significantly flatten the center of the distribution of future economic growth rates and distribute this weight to the tails. Or in Weitzman's words, "people are acting in the aggregate as if there is much more marginal-utility-weighted subjective variability about future growth rates than past observations seem to support." (Weitzman, 2007, p. 1).

132. Though imperfect, this observation would appear to be a potentially useful guide to the construction of future expectations with respect to climate change. Helpfully, Weitzman provides rough empirical orders of magnitude. Specifically, US investors behave as if the standard deviation of fundamental economic volatility, defined as the volatility of aggregate consumption, were more than eight times larger than historical data series would suggest. In other words, investors, in their projection of the future distribution of outcomes, subjectively

expand the historical variance of consumption growth by a factor of roughly 70. This massive expansion in variance neatly explains the three aforementioned puzzles.

133. The translation of these insights into the climate adaptation problem at hand is far from straightforward. For example, while truly catastrophic economic outcomes could be expected to render the distinction between safe and risky investments moot, the distinction is likely to maintain far into the left tail of the distribution of economic outcomes. On the other hand, in Ethiopia, the impacts of truly dismal climate outcomes are likely to be similar regardless of policies pursued. As a result, there may be little information in the far left tail that would have significant content for public decision-making. There is also the related issue of motivating public decision-making on the basis of aggregate observed behavior of investors. Nevertheless, the fundamental point remains—rational decision-makers who must construct subjective prior distributions of outcomes of nonergodic systems significantly flatten and expand the distribution of historical outcomes.

134. Our choices are presented in Table 17 and Figure 2. The row of Table 17 labeled "Historical" shows the distribution of estimated climate impacts on agricultural value added. The figures were derived by averaging the estimated percent productivity shocks across commodities, obtained from the historical data via the regression analysis described above, using 2001 shares in agricultural value added as weights. The resulting average provides an estimate of the direct impact of climate variation on agricultural value added as a whole. The table divides the distribution of agricultural sector outcomes into six equally weighted parts and presents the mean impact on total value added for each part. Note that weight in the distribution shifts to more extreme outcomes.

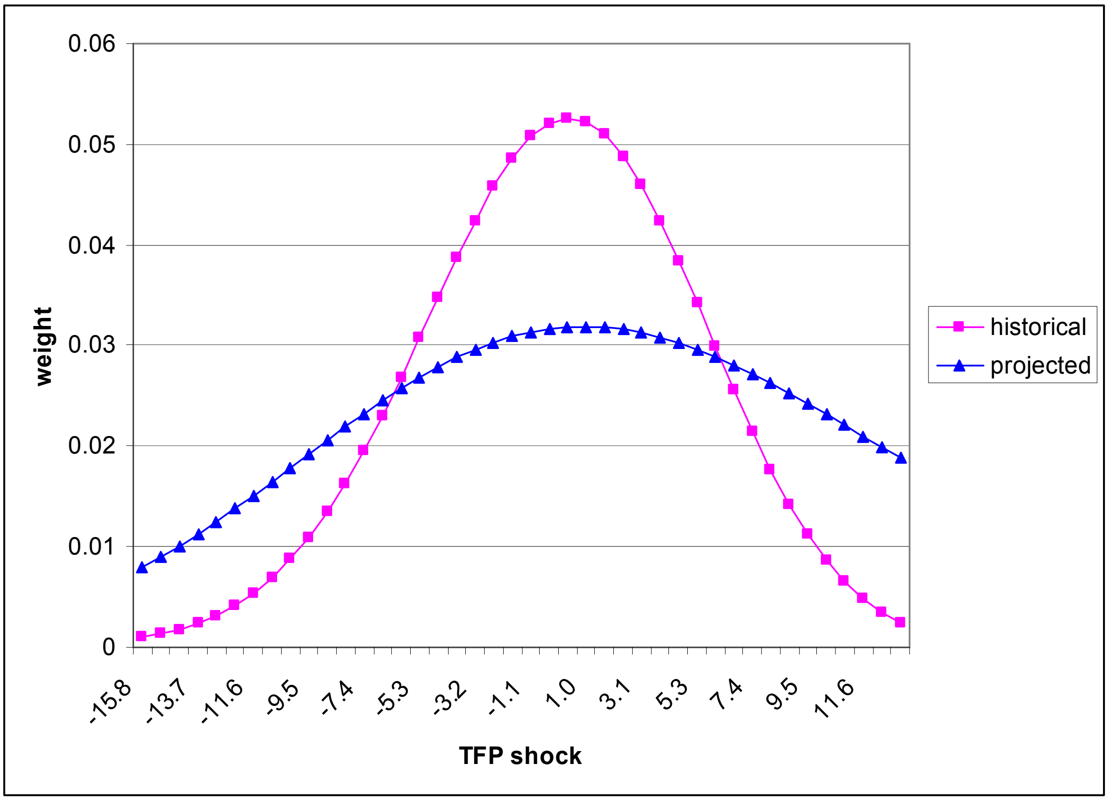
Table 17: Implications of Climate Outcomes for Total Agricultural Value Added
(% difference from trend by probability tranche)

	Lower					**Upper**
	0<π<1/6	**1/6< π <1/3**	**1/3< π <1/2**	**1/2< π <2/3**	**2/3< π <5/6**	**5/6< π <1**
Historical	-7.3	-3.6	-1.2	1.0	3.0	8.1
Projected	-11.0	-4.1	-1.3	1.6	5.2	11.2

135. Figure 2 provides another perspective on the same phenomena. It shows a smoothed estimated distribution function for the impact of climate outcomes on total agricultural value added. Similar to Table 17, Figure 2 shows that, despite high volatility, the mass of probability remains near the mean using historical information. Note that the projected distribution more closely resembles the uniform distribution. Weight has been shifted from the center of the distribution towards more extreme outcomes. This is consistent with the discussion above.

136. It is important to emphasize that a choice of a projected distribution that looks more similar to the historical distribution would reflect (i) a greater confidence in the information content of historical outcomes, despite widespread evidence that climate is changing and (ii) a belief that the tendency for climate outcomes to shift towards the extremes of the distribution is not likely to be realized within the time frame of the analysis.

Figure 2: Smoothed Distribution Functions for Variation in Agricultural Value Added Due to Climate Outcomes.



137. The choice of a fairly pronounced shift towards the uniform distribution also provides the opportunity to consider the potential impacts of climate change. In the following economic analysis, the differences in economic outcomes stem primarily from this shift in the distribution of climate outcomes. If the distribution of projected climate outcomes were assumed to remain very similar to the historical distribution, then the implications of climate change for the economy of Ethiopia would be small.

138. The details on the procedure employed to derive the projected distribution follow. To start, two potential deficiencies in the FAO production index data employed for this analysis were addressed. First, as mentioned above, political events can cause changes in production levels or reported production levels. For Ethiopia, political shifts in 1992 are associated with reported declines in production levels for some important crops. These shifts do not accord with GDP growth numbers, which are positive. The production declines may (or may not) be statistical anomalies. Second, some more difficult to measure products, such as vegetables and fruits and indigenous meats register very stable production patterns over time. Experience in other developing countries indicates that, particularly for difficult to measure products, statistical offices have a fairly strong tendency to simply report a relatively stable rate of growth in production. This is true even though these sectors occupy a fairly large share of total agricultural value added. The first factor, if an error, would overstate variance while the second factor would tend to understate variance.

139. In the sensitivity analysis, data for the years 1993 and 1994 are substituted with uniform declines in production of 14% and 8% across all commodities for each year respectively. These points are designed to eliminate the potentially false readings from 1993

(which carry to 1994 due to the lag structure of the econometric model) and increase the variance of suspiciously stable sectors as well as injecting a higher degree of positive covariance with sectors exhibiting high volatility such as cereals (where a -14% realization is fairly common).

140. Based on the estimated error terms using the adjusted data, an information theoretic procedure was employed to reweight each possible outcome such that the projected distribution reflects enhanced variance (33% greater standard deviation) and the observed small positive skewness in the historical distribution was set to zero. Golan, Judge, and Miller (1996) provide a detailed treatment of information theory and moment constraints. The result is greater weight in the tails of the distribution. While reweighted, the points in the distribution remain historical observations with more extreme outcomes having a higher probability of being observed. The implications of these events across commodities remain constant implying that fundamental observed covariance relationships are preserved though the estimated covariance of the distribution changes due to the reweighting. This property reflects the assumption that, if a particular climate realization affected commodity A in a strong negative manner and commodity B in a slight positive manner, then the same climate realization in the future would have similar impacts on commodities A and B.

141. Relative to the variance expansion factors unveiled by Weitzman, the variance expansion employed to develop the prior distribution of future outcomes is small. Physical limits on positive realizations and practical decision-making limits on negative outcomes rationalize the smaller numbers. Specifically, it appears unlikely that climate change will result in positive outcomes well beyond the realm of historical experience. And, as mentioned above, policy options to confront severely negative outcomes are likely highly constrained. Hence, for the purposes considered here (adaptation decisions), these outcomes are ignored with implications for the domain of potential outcomes considered and the variance of the prior subjective distribution.

142. In closing this subsection, it is perhaps worthwhile to note that more sophisticated methods for characterizing future distributions are in process. For example, one could use models of crop growth calibrated to Ethiopian conditions, which take as inputs meteorological data (rainfall, consecutive dry days, temperature, soil moisture, etc.) derived from global circulation models (GCMs) of the earth's climate. By linking these two structural models, one can hope to obtain further insight into the implications of climate change for agricultural production.

143. While these methods are more sophisticated and potentially useful, they do not alter the need for careful consideration of the final subjective prior distribution of future climate outcomes. Like economic models, GCMs are simplifications of reality built to capture the primary forces driving historical realizations. Considerable uncertainty exists as to their performance under conditions of unprecedented (within the domain of historical application of the model) and growing atmospheric CO_2 concentrations. Furthermore, as Weitzman (forthcoming) points out, significant effort has been expended to determine the likely mean impact of greenhouse gases. However, recent research is revealing that decision-making is most likely to be driven by assessment of extremes. Existing models may do relatively well in representing mean impacts but poorly in their representation of extreme events. Consequently, while improved information about the likely distribution of future climate outcomes is always desirable, the need to develop a subjective prior distribution of future climate outcomes will remain.

8. CLIMATE SHOCKS AND ADAPTATION: SIMULATION RESULTS

8.1 Scenarios

144. The focus in this section is on identifying the implications of climate shocks on economic performance and how they might be ameliorated through various adaptation measures. Some autonomous adaptation and coping strategies are built into the model, while others require modeling of longer-term changes in investment strategies. Some adaptation by farmers within the individual agricultural activities is already built into the estimates of productivity impacts derived from the crop simulation and Ricardian studies reviewed in section 4. Moreover adaptation in the form of migration of workers to other sectors in response to climate-related productivity shocks is endogenously determined in the simulation analysis by allowing inter-sectoral labor mobility as are consumption responses to climate-induced relative price changes on the demand side.[35]

145. In the model, a climate shock involves changing various productivity parameters and capital stocks, and then producers are assumed to be able to re-optimize given the changes. For example, given a drought, farmers are assumed to be able to adjust factor inputs (e.g., use less intermediate inputs) rather than have their yield simply be less than expected. The model thus incorporates anticipative adaptation, which is probably an optimistic assumption, given the unexpected nature of many climate shocks.

146. Initial parameters in the model are first calibrated to the 2001/02 SAM-based benchmark dataset, such that the model equilibrium for the initial period exactly replicates the benchmark. A base dynamic simulation is then constructed which involves specification of annual time paths for labor force and arable land growth, productivity growth by production activities, government expenditure, and trade balances over the 25 year simulation horizon. In principle, dynamic simulation runs also allow the specification of alternative relative world market price trends, although they are fixed in the runs described below.

147. The sectors and factors of production used in the CGE model are presented in Table 18. All the agricultural detail in the underlying Social Accounting Matrix (SAM) has been retained, while the industrial sectors and some service sectors have been aggregated.

148. The CC-CGE model incorporates stochastic elements, as described in the previous section. For each dynamic simulation, the model is solved repeatedly (thirty times) for the twenty-five year period with different random draws of sectoral productivity parameters for each agricultural activity in all years. The random draws are from the empirical joint distributions based on historical data, and so reflect actual historical distributions of shocks rather than fitted distributions. For these Monte Carlo simulations, we compute the means and standard deviations of the results for all endogenous variables.

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[35] The prototype model does not incorporate institutional and cultural constraints on rural-urban migration in Ethiopia. For a brief discussion of such potential constraints see World Bank (2007: Box 11).

Table 18: CGE Model, Sectors and Factors of Production

	Sectors:		Factors
Agriculture	**Industry**	**Services**	**of production**
Teff	Mining	Construction	Agricultural labor
Barley	Petroleum & coal	Trade	Unskilled labor
Wheat	Final mfg	Transport & comm	Skilled labor
Maize	Intermed mfg	Financial services	Land
Pulses	Utilities	Other services	Capital
Coffee		Public admin	
Vegetable and fruit		Education & health	
Oil seeds			
Other cash crops			
Other crops			
Other agriculture			
Source: EDRI SAM for Ethiopia.			

149. Climate shocks are assumed to have asymmetric impacts on productivity and sectoral capital stocks. A positive climate shock in a given year and agricultural sector increases sectoral factor productivity. A negative shock to productivity in a particular agricultural sector is assumed to result in a decrease in the rate of growth of productivity in that year and also in the destruction of the some of the installed capital in the sector. In effect, the negative climate shock is assumed to result in additional depreciation of sectoral capital for the year in which the shock occurs, which results in less aggregate growth of the capital stock for a given level of investment than would otherwise have occurred. Given that the use of livestock for plowing dominates Ethiopia's agriculture, droughts frequently kill cattle, effectively destroying productive assets in an important sector of the economy. Moreover, although their frequency and impacts may not be as intensive as droughts, floods may also destroy infrastructure, resulting in similar effects.

150. Six experiments are reported and discussed below, a deterministic base run and five stochastic scenarios, which are designed to demonstrate the feasibility and robustness of the modeling methodology.

151. The simulations are designed to explore the potential negative impact of climate shocks, in the absence of investments designed to ameliorate them. The six experiments are:

- Base run with deterministic outcomes—no stochastic shocks. Exogenous labor force and land growth, and exogenous trends on productivity growth in all sectors.
- Sim 1: Historical pattern of agricultural productivity variability, drawing sectoral agricultural productivity shocks due to climate shocks from the historical record.
- Sim 2: Increased variance of agricultural productivity shocks by increasing the weight of extreme shocks in sampling from the historical record. Standard deviation of productivity shocks increases by 41%. Essentially no shift of mean.
- Sim 3: Sim 2 plus negative 5% shift in the mean of productivity shocks.
- Sim 4: Sim 3 plus increased standard deviation of shocks by 34% (multiplying each shock by 1.34, increasing variance by 80%).
- Sim 5: Sim 2 plus negative 10% shift in mean productivity shocks and increased variability only of negative shocks (multiplying each negative shock by 1.34).

152. The first stochastic simulation, Sim 1, essentially reproduces the historical stochastic experience of Ethiopia, and the results compared to the base run indicate the importance of using a stochastic rather than a deterministic model. The remaining simulations assume various negative climate shocks. The second, Sim 2, assumes that the shocks are within the historical boundaries, but with more frequent large shocks chosen from the historical record. The third, Sim 3, shifts the distribution away from the historical record, assuming a 5% negative shift in the mean of the agricultural productivity shocks in addition to increased sampling weight on extreme shocks, as in Sim 2. Simulations 4 and 5 also start from Sim 2, but postulate different changes in the historical distribution. Sim 4 shifts the mean as in Sim 3, and also assumes increased variability. Sim 5 assumes a larger negative shift in the mean of the shocks (negative 10%) and increased variability of the negative shocks.

The assumed negative mean shifts are broadly in the range suggested by the predictions of Ricardian and crop simulation studies reviewed in section 5.

8.2 Simulation Results for Climate Shocks

8.2.1 Real Macro-Aggregates

153. Table 19 provides data on aggregate growth rates. The base run generates a 7.48 percent average annual real GDP growth rate over 25 years.[36] As discussed in section 2, Ethiopia's economy has grown at over 10 percent per year over the last five years (2003/4 – 2007/08) and its overarching policy strategy, the PASDEP, also outlines various growth scenarios and the investment needs and policy course required to achieve them. Private and government consumption grow at 6.9 and 6.4 percent respectively, while aggregate investment grows at 7.5 percent, somewhat faster than the other macro aggregates. The various climate shocks lower these growth rates significantly, especially with shifts of the mean to negative shocks. The historical record with more variation, Sim1, has a relatively minor impact on growth rates—if the future is like the past, but with just increased variation, the impact of climate shocks on average growth rates is modest. The impact on variation of growth rates, however, is significant and is discussed below. As the variance increases and the shocks become more negative, the impact is much more serious. The worst case scenario, Sim5, results in growth rates two and a half percentage points lower than in the deterministic base run.

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[36] According to a World Bank assessment of the economic consequences of achieving the MDGs in Ethiopia using the MAMS dynamic CGE model, an average real GDP growth rate of about 7 percent is necessary for Ethiopia to achieve most of the MDGs by 2015. See Lofgren and Diaz-Bonilla (2006) and Ahmed, Diaz-Bonilla, Lofgren, and Robinson (2006).

Table 19: Growth Rates of Real Macro Aggregates

Macro Aggregates	Base	Sim1	Sim2	Sim3	Sim4	Sim5
Consumption	6.93	6.63	6.54	5.42	5.35	4.18
Investment	7.49	7.25	7.19	6.07	6.01	4.78
Government	6.41	6.27	6.23	5.43	5.40	4.53
Exports	10.09	9.79	9.70	8.24	8.17	6.58
Imports	6.95	6.69	6.61	5.39	5.33	4.07
Absorption	6.96	6.69	6.63	5.55	5.49	4.35
GDP	7.48	7.19	7.13	6.01	5.94	4.75

Note: *Base:* baseline simulation in the absence of any climate-related shock. *Sim1*: historical sample distribution. *Sim2*: double historical variance plus negative 20% shift of mean. *Sim3*: 25% increase in Sim2 shocks plus 25% negative shift of mean. *Sim 4*: Sim 3 plus increased standard deviation of shocks by 34%. *Sim 5:* Sim 2 plus negative 10% shift in mean productivity shocks and increased variability only of negative shocks

154. Table 20 shows the decomposition of the sources of growth, using aggregate data from the simulations and applying the simple Solow growth decomposition methodology. Factor growth rates are weighted by factor shares in real value added, and the weighted sum is subtracted from the aggregate growth rate of GDP at factor cost.[37] The difference, or residual, is attributed to total factor productivity (TFP) growth.

155. By assumption, labor by skill category and land all grow at the same rates across the simulations. The capital stock grows at significantly lower rates, as progressively more negative and larger climate shocks are assumed. In particular, the shocks that negatively shift the mean of productivity shocks, Sim3 to Sim5, have much larger impacts on growth. While the shocks lead to slower rates of TFP growth, the share of the contribution of TFP growth to aggregate growth remains roughly the same across the simulations, except the most extreme Sim5. The contribution of capital, however, declines the most across all the simulations.

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[37] Note that real GDP at factor cost grows at a slightly different rate than real GDP at market prices.

Table 20: Solow Growth Decomposition - Contributions to Growth (percent)

Factors	**Base**	**Sim1**	**Sim2**	**Sim3**	**Sim4**	**Sim5**
Unskilled labor	2.61	2.72	2.74	3.26	3.29	4.12
Skilled labor	9.26	9.62	9.71	11.54	11.66	14.60
Agricultural labor	4.06	4.22	4.26	5.06	5.12	6.41
Capital	37.58	36.33	35.89	31.17	30.78	23.12
Land	1.53	1.59	1.61	1.91	1.93	2.42
TFP	44.95	45.52	45.80	47.05	47.23	49.33
GDP at factor cost	100.00	100.00	100.00	100.00	100.00	100.00

Factor and TFP Growth Rates (percent)

Factors	**Base**	**Sim1**	**Sim2**	**Sim3**	**Sim4**	***Sim5***
Unskilled labor	2.50	2.50	2.50	2.50	2.50	*2.50*
Skilled labor	2.50	2.50	2.50	2.50	2.50	*2.50*
Agricultural labor	2.50	2.50	2.50	2.50	2.50	*2.50*
Capital	7.27	6.77	6.63	4.84	4.73	*2.84*
Land	1.00	1.00	1.00	1.00	1.00	*1.00*
TFP	3.44	3.35	3.34	2.89	2.87	*2.39*
GDP at factor cost	*7.65*	*7.36*	*7.30*	*6.14*	*6.07*	*4.85*

Note: TFP is total factor productivity growth

156. Table 21 presents the coefficient of variation (CV, standard deviation divided by the mean, in percent) for the macro aggregates for selected years for the three simulations. As expected, the variation increases across simulations 1-4, with increased variability of climate shocks generating increased variability in economic performance. In Sim 5, the increase in variability is assumed to occur only for negative shocks, so that the overall variance is less than in Sim 4. Aggregate consumption always has a higher CV than the other macro aggregates; while government and investment expenditure have lower values. The burden of adjustment appears to fall more heavily on consumers, which is to be expected since the productivity shocks all occur in agriculture, most of which is used for consumption. The CV for aggregate absorption is always smaller than for real GDP, indicating that international trade serves to dampen the impact of climate shocks on aggregate demand. There does not appear to be any trend in the coefficients over time, which is to be expected since there is not assumed to be any efforts to invest in adaptation technologies that would mitigate the impacts of the climate shocks and there is no trend assumed in the variability of climate change shocks.

Table 21: Coefficient of Variation (CV) of Macro Aggregates

		Simulation				
Year	**Macro aggregate**	**Sim1**	**Sim2**	**Sim3**	**Sim4**	**Sim5**
5	Consumption	2.64	3.71	3.89	5.22	4.78
	Investment	1.05	1.15	1.17	1.77	1.33
	Government	0.65	0.79	0.85	1.17	1.14
	Exports	5.88	6.28	6.62	10.22	7.43
	Imports	2.64	2.86	2.89	4.52	3.10
	Absorption	1.97	2.75	2.88	3.90	3.55
	GDP	2.27	3.16	3.33	4.51	4.13
15	Consumption	2.87	3.28	3.74	5.01	5.03
	Investment	1.07	0.96	1.11	1.51	1.51
	Government	0.59	0.62	0.81	1.12	1.24
	Exports	1.36	1.40	2.02	2.76	3.59
	Imports	1.02	1.05	1.40	1.91	2.24
	Absorption	2.09	2.36	2.71	3.64	3.67
	GDP	2.20	2.50	2.90	3.89	3.99
25	Consumption	2.29	2.68	2.88	3.82	3.75
	Investment	1.28	1.41	1.48	1.94	1.82
	Government	0.52	0.67	0.77	1.01	1.04
	Exports	1.17	1.43	1.58	2.06	2.23
	Imports	1.03	1.25	1.32	1.72	1.75
	Absorption	1.79	2.07	2.19	2.90	2.82
	GDP	1.84	2.13	2.27	3.00	2.95

Notes: Coefficient of variation is the standard deviation of the variable divided by the mean, in percent.

157. Table 22 shows, in the terminal year, that even a relatively less severe climate change shock (Sim1) causes real GDP to be 6.13 percent lower in the final year relative to the base run. The impacts on final-year GDP are progressively worse as the climate change induced shocks become harsher. In the worst case scenario (Sim5), real GDP in the final year would be 46 percent lower than in the base run.

Table 22: Terminal year: Percent Change of Real Macro-Aggregates from Base Run Value

	Percent change from base Run Value (terminal year)				
Real macro aggregate	**Sim1**	**Sim2**	**Sim3**	**Sim4**	**Sim5**
Private consumption	-6.81	-8.25	-28.92	-30.03	-46.42
Fixed investment	-5.17	-6.49	-27.44	-28.33	-45.83
Government consumption	-3.06	-3.91	-19.86	-20.50	-34.77
Exports	-6.39	-8.15	-33.43	-34.43	-54.08
Imports	-5.65	-7.21	-29.66	-30.55	-48.02

Absorption	-5.96	-7.30	-27.40	-28.40	-44.75
GDP	-6.13	-7.51	-28.16	-29.19	-45.98
Note: The terminal year is 25 years from the initial year.					

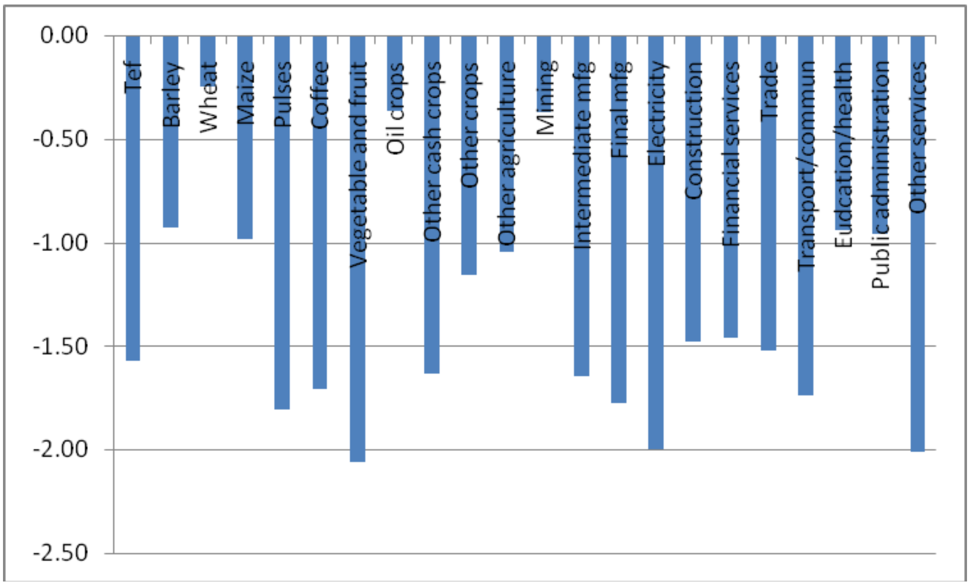
158. The implications of this huge real GDP differential are significant. Even a small differential in growth rates is consequential over a long time horizon.

8.2.2. Sectoral Performance

159. Figure 3 plots the changes in mean sectoral growth rates relative to the deterministic base run for Sim 4, which assumed a negative shift of 5% in the mean of the distribution of agricultural productivity shocks and an increase in overall variability. While the productivity shocks occur only in the agricultural sectors, the negative impact is spread across the economy. The results indicate the importance of using an economy-wide framework for analyzing the impact of climate change shocks, even if the shocks are largely focused on a few sectors. The indirect effects arising from productivity shocks are as important as the direct effects.

160. Table 23 shows the agricultural share of aggregate real value added (real GDP at factor cost) for selected years. In all the experiments, the total share of agriculture value added declines, as would be expected in a rapidly growing developing country. With the robust growth rate of 7.48 percent (Base), the share of value added in agriculture falls about fifteen percentage points, which indicates a rapid rate of structural change. Productivity shocks which reduce the growth rate also reduce the rate of structural change.

Figure 3: Changes in Sectoral Growth Rates (percentage points), Sim 4



161. Table 24 shows that the share of labor input in agriculture declines faster than under the climate shock scenarios that have larger negative effects on mean growth rates (Sim3 to Sim5). The agricultural shares of skilled and unskilled labor inputs in the base run scenario fall by about ten percentage points relative to the first year. On the other hand, the agricultural shares in the other three scenarios (Sim1 to Sim3) fall by about five percentage

points, indicating much less labor migration in these scenarios. The results indicate that the share of capital in agriculture increases in all the simulations. This result comes from the assumption that capital embodied technical change is high in agriculture, reflecting the view that Ethiopia has potentially high returns to investment in agriculture. For example, major infrastructure investment in rural roads and water systems generates externalities across all agricultural activities.

Table 23: Agriculture Share of Aggregate Real Value Added

Year	Base	Sim1	Sim2	Sim3	Sim4	Sim5
Year 1	46.24	46.31	46.80	46.85	47.13	46.64
Year 5	42.72	42.69	43.10	44.45	44.68	45.82
Year 10	38.81	39.09	38.81	41.02	41.16	43.54
Year 15	35.51	35.39	35.59	38.00	38.09	41.00
Year 20	32.86	32.89	32.87	35.07	35.16	37.99
Year 25	30.86	30.28	30.23	31.94	31.83	34.21

Table 24: Agricultural Share of Factor Employment

		Simulation					
Yr	Factor	Base	Sim1	Sim2	Sim3	Sim4	Sim5
1	Agricultural labor	100.00	100.00	100.00	100.00	100.00	100.00
	Unskilled labor	69.25	69.40	69.48	69.53	69.66	69.63
	Skilled labor	20.92	21.10	21.20	21.28	21.47	21.45
	Capital	16.94	17.10	17.26	17.29	17.47	17.39
10	Agricultural labor	100.00	100.00	100.00	100.00	100.00	100.00
	Unskilled labor	65.53	65.82	66.00	67.36	67.61	69.03
	Skilled labor	16.88	17.16	17.33	18.69	18.97	20.61
	Capital	22.57	21.97	21.92	19.15	19.16	16.42
25	Agricultural labor	100.00	100.00	100.00	100.00	100.00	100.00
	Unskilled labor	58.75	59.85	60.04	62.32	62.54	64.85
	Skilled labor	12.21	12.85	12.96	14.44	14.61	16.41
	Capital	34.25	32.90	32.40	27.01	26.66	21.13

162. From Table 25, the growth rate of factor wages also indicates that labor wages under the base run scenario grow much faster than in the stochastic simulations. Moreover, the wage differentials in the terminal year between the base run and the other scenarios become larger as the climate shocks become more severe. For instance, from Table 26, the wage of agricultural labor in general shrinks by 34 percent in the terminal year under the most severe climate change shock (Sim5) relative to the base run. The impact of the climate change is harsher on the wages of skilled labor as opposed to the unskilled.

163. The very low and relatively stable growth rate of the capital rental rate in the base run and Sim1 and Sim2 reflect the fact that capital has significant embodied technical change. As the capital growth rate falls in the simulations with larger productivity shocks, the rental rate of capital rises. Capital becomes scarce relative to other factors, and the rental rate increases relative to the base run.

Table 25: Growth Rates (%) of Factor Wages

Factors	Base	Sim1	Sim2	Sim3	Sim4	Sim5
Agricultural labor	3.67	3.44	3.41	2.65	2.58	1.69
Unskilled labor	4.15	3.85	3.81	2.92	2.83	1.84
Skilled labor	4.96	4.57	4.52	3.44	3.34	2.17
Land	5.06	4.77	4.72	4.09	4.00	3.28
Capital	0.04	0.10	0.17	0.75	0.75	1.42

Table 26: Percent Change of Factor Wages from Base in Terminal Year

Factors	Sim1	Sim2	Sim3	Sim4	Sim5
Agricultural labor	-5.18	-5.74	-21.12	-22.48	-37.06
Unskilled labor	-6.62	-7.42	-24.75	-26.23	-41.52
Skilled labor	-8.56	-9.65	-29.55	-31.20	-47.61
Land	-6.45	-7.32	-19.82	-21.52	-33.63
Capital	1.32	3.05	18.40	18.28	38.90

8.3 Sensitivity Analysis

164. A number of simulations were done to test the robustness of the results concerning the impact of climate shocks to different assumptions about the underlying parameters and trends. Three different issues were explored concerning sensitivity to: (1) different underlying growth rates, (2) choice of time horizon, (3) different aggregations of the agricultural sectors from the SAM.

165. Lower rates of productivity growth (both disembodied and embodied in land and capital) for both agricultural and non-agricultural sectors were chosen to generate a calibrated growth rate of GDP in the base run of about five percent. Climate change shock simulations were run against this base. The results indicate that the impact of climate shocks is similar, but relative to the lower base run growth rates.

166. To test for sensitivity to time horizon, the various experiments were repeated for thirty years instead of twenty-five. There was essentially no change in the impact on growth rates.

Results for the terminal year, of course, differ because of the longer time horizon, but comparisons across the simulations were essentially similar to the twenty-five year period.

167. The sensitivity of the variability results to changes in the historical distribution of climate shocks indicates the importance of analyzing the explicit mechanisms through which climate shocks affect productivity in the agricultural sectors. Without such analysis, it is difficult to capture accurately the asymmetries of the impacts of negative and positive climate shocks on economic performance, which are very important in determining both average and variance of the impacts.

168. To test for sensitivity to aggregation, a version of the model was implemented with the eleven agricultural sectors aggregated to five. The stochastic draws were also aggregated. The results were strikingly different, with far less effect from climate change shocks. The problem is that the aggregation eliminated the covariation across shocks affecting the various agricultural sectors, so that the impacts were essentially dampened by the averaging. The results indicate the importance of using as much agricultural detail as is needed to capture the links between climate change shocks and particular sectors.

169. In the modeling framework used here, the lack of explicit linkages between changes in climate variables such as temperature and rainfall and outcomes in agriculture also limits our ability to analyze the impact of possible investments designed to ameliorate or offset the impacts of climate shocks. In the next section, we discuss such adaptation strategies and how they might be introduced into models.

8.4 Adaption to Climate Change Shocks

8.4.1 Adaptation Strategies

170. Adaptation to climate change is vital if developing countries in general and Ethiopia in particular are to cope, while also seeking to meet the Millennium Development Goals (MDGs). Adaptation policies designed to reduce vulnerability to climatic change are more likely to succeed if they are integrated with efforts aimed at poverty reduction and general economic growth strategies. Vulnerability to adverse climate change is a function of geographical exposure, sensitivity and adaptability. Ethiopia, located in a notoriously drought prone region, heavily dependent on rain-fed agriculture, with fragile eco-systems and very low per-capita income, scores poorly in all three respects.

171. Adaptive capacity improves with growth in per-capita income, infrastructure stock, and the level of development in general. Good adaptation policies are thus likely to be synonymous with good development strategies. As Stern (2007) puts it, "much of what governments should do in relation to adaptation is what they should be doing anyway—that is, implementing good development practice". The empirical results from the various simulations give some indirect indications about potential elements of successful adaptation strategies.

172. Under the base scenario, the share and the value of agriculture value added are much larger than in the climate shock scenarios, while at the same time, it utilizes lower labor inputs. This indicates a rise in agriculture productivity, which is due to the large assumed investment in areas that increase the sector's productivity. For instance, investment in

irrigation and road infrastructure raises the sector's productivity as well as the overall economy.

173. The relative weakness of the non-agricultural sectors to absorb surplus labor remains one of the dominant challenges to successfully mitigate the impacts of climate change. A successful adaptation policy would encourage greater migration from agriculture into other sectors that pay more and are less affected by climate variability. As the empirical results indicate, accelerated economic growth increases labor migration from agriculture to the non-agriculture sectors, and climate shocks yield slower growth and less structural change.

174. A useful distinction, suggested by Lecocq and Shalizi (2007), is the distinction between reactive adaptation that focuses on coping with the adverse impacts of climate change *ex post* after they occur, and anticipative adaptation that focuses on lowering the costs of coping *ex ante*. The latter encompasses measures taken in advance to limit the unavoidable consequences resulting from climate change and/or to reduce the extent of reactive adaptation required when climate change shocks materialize

175. Given Ethiopia's experiences of frequent episodes of drought and heavy dependence on rain-fed agriculture, an important element of an anticipative adaptive strategy is to accelerate investments in water harvesting and water storage capacity, along with investment in irrigation and roads. The recently published World Bank Country Water Resources Assistance Strategy for Ethiopia describes the prospective elements of such an investment program in detail.[38] This strategy also emphasizes investments in road transport infrastructure as a means to reduce vulnerability to climate variability—though climate variability is not associated with global warming in this document. Notably, without any reference to global warming or climate change adaptation, the World Bank document affirms the validity of the Stern analysis cited above. The strategy document points out that

176. "…unmitigated hydrological variability currently costs the economy more than one-third of its growth potential. The very structure of the Ethiopian economy with its heavy reliance on rain fed subsistence agriculture makes it particularly vulnerable to hydrological variability. Its current extremely low levels of hydraulic infrastructure and limited water resources management capacity undermine attempts to manage variability. These circumstances leave Ethiopia's economic performance virtually hostage to its hydrology. ... Current limited access to transportation and markets undermines incentives for surplus agricultural production and reinforces the highly vulnerable subsistence-oriented structure of the economy. ... Today 90 percent of Ethiopia's roads are dry weather roads that cannot be used effectively during the four-month-long wet season. The reliance of the economy on this small network of mostly dry-weather roads makes commerce highly vulnerable to floods and heavy rainfall. ... The combination of water, irrigation, hydropower, roads and other market infrastructure investments should produce dramatic synergies, and provide the incentives and opportunity for farmers to shift out of subsistence agriculture into surplus/commercial agriculture and non-agricultural activities."[39]

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[38] World Bank (2006). The National Adaptation Plan of Action (NAPA) for Ethiopia (Tadege (ed), 2007) likewise assigns a high priority to the development of small-scale irrigation and water harvesting schemes as well as to a large-scale water development project in the Genale-Dawa basin. These two proposed projects alone account for $ 730 million of the total estimated cost of $ 770 million for all top-priority adaptation measures identified in the NAPA.

[39] World Bank (2006)

177. While persuasive, in order to provide information on the macro impacts of such programs, it is necessary to capture such links in formal models.

8.4.2 Modeling Adaptation

178. The simulation of an adaptation strategy that scales up existing investment plans of this type as indicated by the large real investment growth is relatively straightforward, although empirical estimates of the impact of such investment on vulnerability to climate shocks requires detailed analysis at the sectoral level. Other adaptation measures commonly identified in the literature are support for the adoption of new climate-resilient cultivars and livestock varieties, support for local R&D efforts to produce more resilient crops. The direct costs and likely direct productivity impacts of these investments are also readily quantifiable, but require country-specific analysis.

179. To illustrate, Diao et al (2005, 2007) and Fischer et al (2002) are sources of recent estimates of productivity increases from irrigation (up to 40% for cereal grains) for Ethiopia. Comparisons of Ricardian studies for drylands and irrigated land provide a further source for the quantification of gains. The direct productivity impacts of investments in road infrastructure can be captured in the model as cost-reducing reductions in transport margins. On the cost side, Inocencio et al (2005) estimate the unit cost per ha for new irrigation construction projects in SSA at US$ 14,455 in 2000 prices including US$ 10,475 hardware costs. The same study reports an average gestation period of 40 months, which can also be captured in the dynamic analysis. Potential further sources for recent detailed cost estimates of comparable projects are the NAPAs (National Adaptation Plans of Action) of Ethiopia and neighboring countries.

180. Bouzaher, Devarajan and Ngo (2008) argue that the reason why such a small percentage of cultivated land in Africa is irrigated is that the costs of extending irrigation used to exceed the longer-term benefits, and suggest that the increased threat of climate change may indeed tip the balance in favour of irrigation. A careful quantitative dynamic analysis along the lines proposed above would allow examination of this conjecture.

181. It would be feasible in the CC-CGE model to introduce alternative technologies for the various agricultural sectors that are more resistant to the impact of climate shocks. Such technologies would undoubtedly be more capital intensive, and also intensive in the use of intermediate inputs. By directing investment into these sectors, the model would capture the tradeoff between adopting more expensive but more climate shock resistant technologies over time.

182. All these modeling strategies do not require modeling of the explicit links between particular climate shocks such as changes in average temperature and/or rainfall and economic performance in agriculture. One can use indirect measures of the links through econometric analysis, as done in the studies cited above. Moving toward more detailed models requires disaggregation by crop and agro-climatic region (or watershed), as well as studies of the links between changes in measurable climate variables and agricultural outcomes. Such analysis would greatly enhance our ability to incorporate investment in new adaptation measures into formal models. Since there is little or no historical experience with such measures, it is impossible to estimate their impact using econometric analysis of historical data. A modeling strategy that incorporates engineering and agronomic analysis, rather than summary econometric relationships, is likely to be very fruitful.

SUMMARY

183. This pilot study develops a methodology that provides an economy-wide framework for analyzing economic impacts from climate change and potential adaptation policies in low-income countries with high exposure to adverse consequences of global warming. To accomplish this objective, the paper modifies and extends a dynamic single-country prototype Computable General Equilibrium (CGE) model to include stochastic elements that are characteristic of climate change and a representation of the sectors that are most likely to be affected. To demonstrate the practical feasibility and potential usefulness of the approach, the model is calibrated to a social accounting matrix for Ethiopia and used to assess the potential quantitative impact of climate change on the economic growth prospects of the country over the next 25 years.

184. Ethiopia is heavily dependent on rain-fed agriculture, and its geographical location and topography in combination with low adaptive capacity entail a high vulnerability to adverse impacts of climate change. Ethiopia is historically prone to extreme weather events. Rainfall in Ethiopia is highly erratic, and most rain falls intensively, often as convective storms, with very high rainfall intensity and extreme spatial and temporal variability. Since the early 1980s, the country has suffered seven major droughts, five of which led to famines in addition to dozens of local droughts. Survey data show that between 1999 and 2004 more than half of all households in the country experienced at least one major drought shock. Major floods occurred in different parts of the country in six of the last 20 years. Time series data show a strong observable link between climate variations and overall economic performance.

185. Regional projections of high-resolution general circulation models suggest a rise in mean temperature relative to 2001 by 0.9 to 1.5 ^{o}C for 2030 and by 4 to 8 ^{o}C towards the end of the 21st century. Projections of mean precipitation trends vary widely across different models even in terms of sign, yet seasonal predictions suggest significant drops in rainfall during the planting season.

186. Crop simulation studies as well as econometric studies of climate change impacts suggest a negative impact on agricultural crop productivity in Ethiopia on the order of 5 to 10 percent by 2030 due to changes in mean seasonal temperature and precipitation and more severe impacts towards the end of the century.

187. These estimates do not take account of additional adverse impacts due to potential increased climate variability around mean trends and the associated increase in the frequency of extreme weather events including heat waves, droughts and flooding. Increased climate variability may have stronger adverse impacts than changes in the means of climate variables in the presence of threshold effects, yet the predictions of higher climate variability are subject to a high degree of uncertainty.

188. The focus of the modeling approach proposed in this study is on stochastic elements in general and extreme events in particular. The approach involves "fattening the tails" of historical climate distributions and hence agricultural productivity distributions. This approach is consistent with the most recent analytical contributions to the economics of climate change with a focus on risk and uncertainty. The basic idea is that ignorance about climate change impacts should lead us to project a distribution of climate outcomes that is more uniform than the historical data would indicate. This comes about for two reasons. First,

our high confidence in the existence of climate change combined with our lack of knowledge about the implications of global climate change for climate outcomes in Ethiopia requires us to consider a more uniform and potentially broader distribution of outcomes. Second, the information that we do have with respect to possible implications of global climate change for Ethiopia points to greater weight at the extremes of the distribution.

189. The critical operational question is exactly how and how much the historical distribution should be modified in order to account for climate change. Unfortunately, this is both unknown and unknowable. We have no choice but to develop a subjective prior distribution of future climate outcomes under the knowledge that climate change renders history an imperfect guide to the future. The fundamental point is that rational decision-makers who must construct subjective prior distributions of outcomes of nonergodic systems significantly flatten and expand the distribution of historical outcomes.

190. The stochastic dynamic general equilibrium simulation analysis adopts a Monte Carlo approach on the basis of the modified joint distribution of the factor productivity parameters for the 11 agricultural activities distinguished in the model. For each dynamic simulation, the model is solved thirty times, for the twenty-five year period with different random draws of sectoral productivity parameters for each agricultural activity in all years from the modified historical distribution with and without mean shifts on the order of -5 to -10% percent.

191. Initial parameters in the model are first calibrated to a 2001/02 SAM-based benchmark dataset for Ethiopia, such that the model equilibrium for the initial period exactly replicates the benchmark. A deterministic dynamic baseline simulation is then constructed which involves specification of annual time paths for labor force and arable land growth, trend productivity growth by production activities, government expenditure and other exogenous variables over the 25 year simulation horizon.

192. In the stochastic simulations, climate shocks are assumed to have asymmetric impacts on productivity and sectoral capital stocks. A positive climate shock in a given year and agricultural sector increases sectoral factor productivity. A negative shock to productivity in a particular agricultural sector is assumed to result in a decrease in the rate of growth of productivity in that year and also in the destruction of the some of the installed capital in the sector.

193. The various climate shocks lower growth rates significantly, especially with shifts of the mean to negative shocks. The historical record with more variation has a relatively minor impact on growth rates—if the future is like the past, but with just increased variation, the impact of climate shocks on average growth rates is modest. The impact on variation of growth rates, however, is significant. The worst case scenario results in growth rates two and a half percentage points lower than in the deterministic base run.

194. The impacts on final-year GDP are progressively worse as the climate change induced shocks become harsher. In the worst case scenario, real GDP in the final year would be 46 percent lower than in the base run.

195. While the productivity shocks occur only in the agricultural sectors, the negative impact is spread across the economy. The results indicate the importance of using an economy-wide framework for analyzing the impact of climate change shocks, even if the

shocks are largely focused on a few sectors. The indirect effects arising from productivity shocks are as important as the direct effects.

196. These simulation results indicate that effective adaptation measures are vital if Ethiopia is to sustain the per-capita growth rates required for achieving the Millennium Development Goals. Adaptation policies designed to reduce vulnerability to climatic change are more likely to succeed if they are integrated with efforts aimed at poverty reduction and general economic growth strategies.

197. Ethiopia's high level of unexploited water resource management potential and low fraction of irrigated land suggest that investments in water resource management infrastructure should be an integral component of a climate change adaptation strategy aimed at the reduction of vulnerability to the effects of global warming. However, a rigorous quantitative analysis of alternative adaptation policy options that would allow the formulation of specific policy recommendations requires further in-depth research into the expected costs and potential benefits of specific adaptation measures and is beyond the scope of this report. Further efforts in this direction, as well as a regional disaggregation of the model into Ethiopia's main agro-ecological zones and a more detailed household disaggregation to facilitate an analysis of poverty impacts, are feasible.

APPENDIX A: Agriculture and the Legacy of Feudalism

1. Ethiopia has witnessed far reaching political, economic and social transformations. Throughout its long history, however, the country retained its essential agricultural character, where tribute and surplus labor were the economic basis of political power.[40] Land tenure policy in Ethiopia had two major characteristics; tributes and tenancy. The peasant occupied land through genealogical decent but paid tributes to the local elite and the government. The tributes were of a diverse nature, the major being appropriation of surplus labor and land-tax, whose value varied according to the degree of cultivation.

2. Traditional land tenure in Ethiopia had had a communal character, with peasants only enjoying usufructuary rights over the land. In the twentieth century, however, a steady process of privatization with implications of sale and mortgage set in.[41] the predominant theme of land tenure in post First World War Ethiopia was an acceleration of the process of privatization. Only in the northern parts of the country did the genealogical system continue to wage a defensive struggle against the influences of privatization. In the south, private tenure increasingly became the norm resulting in large tracts of land concentrated in the hands of the few. For instance, individual holdings as large as 200,000 hectares were recorded in some areas.[42] Conversely in the north, where the genealogical system of land tenure still dominated, the main problems were litigation over land use rights and fragmentation of holdings, as the initial plot was subdivided through successive generations.

3. The most important consequence of the growth of private tenure was the rapid spread of tenancy. Some 50–60 percent of all holdings were estimated to fall under this category, while absentee landlordism, estimated at about 25 percent in the 1960s constituted the other side of the coin.[43] Most tenancy agreements were verbal, involving sharecropping arrangements of one-third, a quarter, or half of the harvest. As the value of land rose, the arrangements tended to be weighted increasingly against the tenant, often culminating in his/her eviction. In addition to the agreed share paid to the landlord, the peasant often had to bear the burden of paying tributes.

4. While post Second World War saw an accelerated privatization of land and the refinement of one of the most advanced and absolute feudal regimes, the period also witnessed widespread opposition against it. Although the elite spearheaded the opposition, it assumed a broader dimension with the outbreak of peasant rebellion in several parts of the country. Their incidence and intensity was much greater than previous rebellions, attesting to the increasingly heavy pressures being exerted on them.[44] In the face of this widespread opposition, the regime failed to implement broad land reforms. This failure bred more opposition. Peasants rose in rebellion and students waged sustained struggle for radical reforms that embraced Marxism-Leninism at its core. Finally, its own soldiers rose against the regime, culminating in the 1974 Ethiopian Revolution.

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[40] Pankhurst (1966)
[41] Zewde (1991)
[42] Zewde (1991)
[43] Zewde (1991)
[44] Zewde (1991)

5. The military junta that took over power in the aftermath of the revolution distributed land to the peasantry but kept ownership in the hands of the government. In line with the Marxist-Leninist ideology that characterized the revolutionary movement, rural Ethiopia was also organized under peasant associations. Nevertheless, with less than 15 percent of the country urbanized, subsistence rain-fed agriculture with little or no aid of modern technology continued to account for a substantial share (as high as seventy percent) of the economy. Moreover, a swelling rural population growing by more than 3 percent annually directly contributed to land fragmentation, deforestation, and degradation. These factors precipitated a steady decline in farm output even as the population skyrocketed. By 1985-86, a combination of a series of droughts, inefficient farming, and the ever deteriorating environment exposed the country to a catastrophic famine, where a staggeringly large number of people starved to death before the world came to the country's aid.

APPENDIX B: The IPCC SRES Scenarios

6. The IPCC published a set of emissions scenarios in 2000 for use in climate change studies (Special Report on Emissions Scenarios—SRES). The SRES scenarios were constructed to explore future developments in the global environment with special reference to the production of greenhouse gases and aerosol precursor emissions. The SRES team defined four narrative storylines, labeled A1, A2, B1 and B2, describing the relationships between the forces driving greenhouse gas and aerosol emissions and their evolution during the 21st century for large world regions and globally. Each storyline represents different demographic, social, economic, technological, and environmental developments that diverge in increasingly irreversible ways. In simple terms, the four storylines combine two sets of divergent tendencies: one set varying between strong economic values (A) and strong environmental values (B), the other set between increasing globalization (1) and increasing regionalization (2).[45] The storylines are summarized as follows:

7. **A1.** The A1 storyline and scenario family describe a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

8. **A2**. The A2 storyline and scenario family describe a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented, and per capita economic growth and technological change are more fragmented and slower than in other storylines.

9. **B1**. The B1 storyline and scenario family describe a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

10. **B2**. The B2 storyline and scenario family describe a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels. (Thornton et al, 2006)

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[45] IPCC-TGICA (2007).

Table B.1: The IPCC SRES Scenarios

Emissions scenario	**Global population (billions)**	**Global GDP[1] (10^{12} US$[1])**	**Per capita income ratio[2]**	**CO_2 concentration (ppm)**	**Global ΔT (°C)**	**Global sea-level rise (cm)**
1990	5.3	21	16.1	354	0	0
2000	6.1-6.2[3]	25-28[3]	12.3-14.2[3]	367[4]	0.2	2
2050						
SRES A1F1	8.7	164	2.8	573	1.9	17
SRESA1B	8.7	181	2.8	536	1.6	17
SRES A1T	8.7	187	2.8	502	1.7	18
SRESA2	11.3	82	6.6	536	1.4	16
SRESB1	8.7	136	3.6	491	1.2	15
SRESB2	9.3	110	4.0	478	1.4	16
IS92a	10.0	92	9.6	512	1.0	–
SRES-max	8.4	59	2.4	463	0.8	2
SRES-min	11.3	187	8.2	623	2.6	29
2100						
SRES A1F1	7.1	525	1.5	976	4.5	49
SRESA1B	7.1	529	1.6	711	2.9	39
SRES A1T	7.1	550	1.6	569	2.5	37
SRESA2	15.1	243	4.2	857	3.8	42
SRESB1	7.0	328	1.8	538	2.0	31
SRESB2	10.4	235	3.0	615	2.7	36
IS92a	11.3	243	4.8	721	2.4	–
SRES-min	7.0	197	1.4	478	1.4	14
SRES-max	15.1	550	6.3	1099	5.8	80

Notes: 1. Gross domestic product (trillion 1990 US$ per year)

2. Ratio of developed countries and economies in transition (UNFCCC-defined Annex I) to developing countries (Non-Annex I)

3. Modelled range across the six illustrative SRES scenarios

4. Observed 1999 value. Calculations in columns 6-7 are relative to 1990. ΔT is change in mean annual temperature averaged across simple climate model runs emulating the results of seven AOGCMs with an average climate sensitivity of 2.8°C.

Source: IPCC-TGICA (2007).

APPENDIX C: Technical Model Description

11. In the following technical description of the dynamic CGE model, variables are capitalized while lower-case notation is used for taste, technology and policy parameters as well as other exogenous constants. Variable and parameter descriptions (except for the share and shift parameters in the various CES aggregators) are provided under the equation block in which they first appear.

12. The calibrated model distinguishes 22 production activities (index set *a*), 24 commodity groups (index set *c*), 2 household groups (index set *h*) and 5 primary factors (index set *f*) as listed in Table A.1. The dynamic simulation runs cover a time period of 25 years (index set *t*).

Trade and Commodity Prices

Export price:

$$PE_{c,t} = PWE_{c,t}(1 - te_{c,t})ER_t \tag{1}$$

Allocation of commodity output between export supply and domestic supply:

$$QXC_{c,t} = at_c\left[\gamma_c QE_{c,t}^{\rho E_c} + (1-\gamma_c)QD_{c,t}^{\rho E_c}\right]^{1/\rho E_c} \tag{2}$$

$$\frac{QE_{c,t}}{QD_{c,t}} = \left[\frac{PE_{c,t}}{PD_{c,t}}\frac{1-\gamma_c}{\gamma_c}\right]^{1/(\rho E_c - 1)} \tag{3}$$

$$PXC_{c,t}QXC_{c,t} = PD_{c,t}QD_{c,t} + PE_{c,t}QE_{c,t} \tag{4}$$

Import price:

$$PM_{c,t} = PWM_{c,t}(1 + tm_{c,t})ER_t \tag{5}$$

Allocation of demand between imports and domestic commodities:

$$Q_{c,t} = aa_c\left[\delta_c QM_{c,t}^{-\rho A_c} + (1-\delta_c)QD_{c,t}^{-\rho A_c}\right]^{-1/\rho A_c} \tag{6}$$

$$\frac{QM_{c,t}}{QD_{c,t}} = \left[\frac{PD_{c,t}}{PM_{c,t}}\frac{1-\delta_c}{\delta_c}\right]^{1/(1+\rho A_c)} \tag{7}$$

$$PQS_{c,t}Q_{c,t} = PD_{c,t}QD_{c,t} + PM_{c,t}QM_{c,t} \tag{8}$$

$$PQD_{c,t} = PQS_{c,t}(1 + ts_{c,t}) \tag{9}$$

PD_c	Price for domestic supply of commodity *c*
PE_c	Domestic price of exports of commodity *c*
PM_c	Domestic price of imports of commodity *c*
PQD_c	Purchaser price of Armington composite commodity Q_c
PXC_c	Producer price dual to composite domestic output QXC_c
PQS_c	Price index dual to Armington composite commodity *c*
PWE_c	World market price of exports of commodity *c*
PWM_c	World market price of imports of commodity *c*
ER	Exchange rate (domestic unit of account per "$")
QXC_c	Domestic production of composite commodity *c*
QD_c	Domestic production of commodity *c* for domestic demand

QE_c	Exports of commodity *c*
QM_c	Imports of commodity *c*
Q_c	Supply of Armington composite commodity *c*
$\sigma E_c = \frac{1}{\rho E_c - 1}$	Elasticity of transformation between export and domestic market production
$\sigma A_c = \frac{1}{1 + \rho A_c}$	Elasticity of substitution between imports and domestic commodity *c*
tm_c	Import tariff rate
ts_c	Sales tax rate
te_c	Export tax rate

Technology, Factor Demand and Activity-Commodity Mapping

Production function

$$QX_{a,t} = amult_{a,t} ax_{a,t} \left[\sum_f \phi_{f,a} \left(adf_{f,a,t} FD_{f,a,t} \right)^{-\rho X_a} \right]^{-1/\rho X_a} \tag{10}$$

Value added per unit of activity output:

$$PVA_{a,t} = PX_{a,t} - \sum_c PQD_{c,t} io_{c,a} \tag{11}$$

Inverse factor demand

$$w_{f,t} = \phi_{f,a} adf_{f,a,t}^{\rho X_a} FD_{f,a,t}^{-(1+\rho X_a)} \left(amult_{a,t} ax_{a,t} \right)^{-\rho X_a} QX_{a,t}^{1+\rho X_a} PVA_{a,t} \tag{12}$$

Aggregator for commodities produced by multiple activities[46]

$$QXC_{c,t} = \alpha_c \left[\sum_a \psi_{a,c} QXAC_{a,c,t}^{-\rho C_c} \right]^{-1/\rho C_c} \tag{13}$$

$$\frac{PXAC_{a,c,t}}{PXC_{c,t}} = \psi_{a,c} \left[\frac{QXC_{c,t}}{QXAC_{a,c,t}} \right]^{1+\rho C_c} \tag{14}$$

$$PX_{a,t} = \sum_c acsh_{a,c} PXAC_{a,c,t} \tag{15}$$

Intermediate input demand:

$$QINT_{c,t} = \sum_a io_{c,a} QX_{a,t} \tag{16}$$

Technical progress:

$$ax_{a,t+1} = FS_{a,t} (1 + gax_{a,t}) \tag{17}$$

$$adf_{a,t+1} = adf_{a,t} (1 + gadf_{a,t}) \tag{18}$$

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[46] The make matrix *QXAC* in the benchmark SAM is largely diagonal except for *c*='chome'. Thus, except for the "home consumption of home production" commodity, (13) boils down to $QXC_c = QXAC_{a,c}$ for the single non-zero (*a*,*c*) pair in each column, and for activities without home production $QX_a = QXAC_{a,c}$ with $PX_a = PXC_c$.

QX_a	Output of activity *a*
$FD_{f,a}$	Cost-minimizing demand for factor *f* by activity *a*
PVA_a	Value added per unit of activity output *a*
$QXAC_{a,c}$	Output of commodity *c* by activity *a* (make matrix)
PX_a	Price of activity output
$PXAC_{a,c}$	Price of commodity *c* from activity *a*
$\sigma X_a = \dfrac{1}{1+\rho X_a}$	Elasticity of substitution between primary factors
$io_{c,a}$	Input of commodity *c* required per unit of activity *a* output
$acsh_{a,c}$	Share of commodity *c* in activity *a* output
$amult_{a,t}$	Temporary climate shock to TFP in activity *a*
ax_a	Total factor productivity(TFP) parameter for activity *a*
$adf_{f,a}$	Efficiency parameter for factor *f* in activity *a*
$gax_{a,t}$	Deterministic trend TFP growth rate for activity *a*
$gadf_{f,a,t}$	Deterministic growth rate of factor *f* efficiency in activity *a*

Income and Final Domestic Demand

Factor income:

$$YF_{f,t} = \sum_a wf_{f,t} FD_{f,a,t} + yffrw_f ER_t \tag{19}$$

Factor income to RoW

$$YFTRW_{f,t} = rwfsh_f YF_{f,t} \tag{20}$$

Household income:

$$YH_{h,t} = \sum_f hfsh_{h,f} YF_{f,t} + trrw_{h,t} ER_t + trgov_{h,t} \tag{21}$$

Household expenditure:

$$HEXP_{h,t} = YH_{h,t}(1 - tyh_h)(1 - S_{h,t}) \tag{22}$$

Optimal household consumption demand (LES):

$$PQD_{c,t} QC_{c,h,t} = PQD_{c,t} qcm_{c,h} + \beta_{c,h}\left(HEXP_{h,t} - \sum_{c'} PQD_{c',t} qcm_{c',h} \right) \tag{23}$$

Government expenditure:

$$EG_t = \sum_c PQD_{c,t} QG_{c,t} + \sum_h trgov_{h,t} \tag{24}$$

Government budget constraint:

$$KAPGOV_t = TAX_t + trrwg_t ER_r - EG_t \tag{25}$$

Government consumption:

$$QG_{c,t} = gstr_{c,t} QGADJ_t \tag{26}$$

Investment demand:

$$QINV_{c,t} = IADJ_t invstr_c \tag{27}$$

YF_f	Total income for factor *f* including factor income from RoW
$yffrw$	Factor income from RoW
$hfsh_{h,f}$	Household *h*'s share of factor *f* income
$trrw_h$	Transfers from rest of the world (RoW) to household *h*
$trrwg$	Net transfers from RoW to government
$trgov_h$	Government transfers to household *h*
$HEXP_h$	Total consumption expenditure by household *h*
S_h	Saving rate of household *h* (adjusts endogenously to maintain S-I balance)
tyh_h	Income tax rate of household *h*
$QC_{c,h}$	Consumer demand for composite commodity *c* by household *h*
$qcm_{c,h}$	LES subsistence consumption parameter
$\beta_{c,h}$	LES marginal household *h* budget share parameter for commodity *c*
$YFTRW_f$	Factor *f* income to RoW
$rwfsh_f$	RoW share in YF_f
EG	Government expenditure
$KAPGOV$	Government saving
TAX	Total tax revenue (equations for determination of tax revenue suppressed)
QG_c	Government consumption by commodity
$QGADJ$	Scaling factor for vector of real government consumption
$gstr_c$	Commodity structure parameter for real government consumption
$QINV_c$	Investment demand by commodity c
$invstr_c$	Commodity structure parameter for real investment demand
$IADJ$	Scaling factor for vector of real investment demand

Capital Accumulation and Labour Endowment Growth

Price of composite investment good:

$$PK_t = \sum_c kcomp_c PQD_{c,t} \qquad (28)$$

Nominal investment expenditure:

$$INV_t = \sum_c PQD_{c,t} QINV_{c,t} \qquad (29)$$

Capital accumulation dynamics:

$$K_{t+1} = K_t(1 - depr) + \frac{INV_t}{PK_t} + \sum_a dkptl_{a,t} FD_{capital,a,t} \qquad (30)$$

Labour force dynamics:

$$FS_{l,t+1} = FS_{l,t}(1 + gf_{l,t}) \quad l \in \{skilled\ labor, unskilled\ labor\} \qquad (31)$$

PK	Price of composite capital good
INV	Nominal investment
$kcomp_c$	Share of commodity *c* in composite capital good
K	$=FS_{Capital}$
depr	Rate of capital depreciation
$dkptl_{a,t}$	Fraction of capital stock in activity *a* destroyed in extreme weather event

Market equilibrium conditions

Factor market clearing:

$$FS_{f,t} = \sum_a FD_{f,a,t} \tag{32}$$

Domestic commodity market clearing:

$$Q_{c,t} = QINT_{c,t} + \sum_h QC_{c,h,t} + QG_{c,t} + QINV_{c,t} \tag{33}$$

Balance of payments:

$$\begin{aligned} kaprw_t \quad = \quad & \underbrace{\sum_c \left(PWM_{c,t}QM_{c,t} - PWE_{c,t}QE_{c,t}\right)}_{\text{Trade balance}} \\ + \quad & \underbrace{\sum_f \left(\frac{YFTRW_{f,t}}{ER_t} - yffrw_f\right)}_{\text{Net factor income}} \underbrace{- \sum_h trrwh_{h,t} - trrwg_t}_{\text{Net transfers}} \end{aligned} \tag{34}$$

FS_f	Total supply of factor *f*
kaprw	Foreign savings (balance of payments deficit – fixed at initial level in all simulations)

Macro Closure

Total saving:

$$TOTSAV_t = \sum_h S_{h,t} YH_{h,t}(1 - tyh_h) + KAPGOV_t + kaprw_t ER_t \tag{35}$$

Final absorption:

$$ABSO_t = \sum_c PQD_{c,t}\left(QG_{c,t} + QINV_{c,t} + \sum_h QC_{c,h,t}\right) \tag{36}$$

$$INV_t = invsh \;\; ABSO_t \tag{37}$$

$$EG_t = govsh \;\; ABSO_t \tag{38}$$

$$S_{Urban,t} / S_{Rural,t} = S_{Urban,0} / S_{Rural,0} \tag{39}$$

TOTSAV	Total savings
ABSO	Nominal absorption
invsh	Fixed investment share of absorption
govsh	Fixed government share of absorption

13. Under this macro closure the share of consumer expenditure in absorption is fixed via (37) and (38) and the household saving rates adjust endogenously. *QGADJ* in (26) adjusts endogenously to enforce (38) and *IADJ* in (27) adjusts endogenously to establish *TOTSAV* = *INV*.

Table C.1: Aggregation Structure of the CGE Model

Actvities a	***Commodities c***	***Description***
atef	ctef	Teff
abar	cbar	Barley
awhea	cwhea	Wheat
amaiz	cmaiz	Maize
apul	cpul	Pulses
avegfr	cvegfr	Vegetables and fruits
aoils	coils	Oil seeds
acash	ccash	Cash crops
acrop	ccrop	Other crops
acoff	ccoff	Coffee
aothrag	cfood	Other agriculture and processed food
*	cenrgy	Petrol, coal and gas
amining	cmin	Mineral extraction
amfg1	cmfg1	Light Manufacuring
amfg2	cmfg2	Other manufacturing
autility	cutility	Utilities
acons	ccons	Construction
atrad	ctrad	Trade services
atrncom	ctrncom	Transport and communication
afserv	cfserv	Financial services
aoserv	coserv	Other services
apadmin	cpadmin	Public administration
aeduhea	ceduhea	Education and health
**	chome	Home production for home consumption
Factors f		***Households h***
Unskilled Labor		Urban households
Skilled Labor		Rural households
Agricultural Labor		
Capital		
Land		

* No domestic production of cenrgy ** chome produced by multiple activities

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