



The Cost of Adapting to Climate Change in Ethiopia: Sector-Wise and Macro-Economic Estimates

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ABSTRACT

This paper uses spatially-explicit analyses of climate change effects on selected key sectors of Ethiopia's economy to estimate both sector-wise and economy-wide estimates of impacts and adaptation costs. Using four IPCC-vetted Global Circulation Models (GCMs) to bracket the uncertainty surrounding future climate outcomes, the paper finds that by 2050 climate change could cause GDP to be 8–10 percent smaller than under a no-climate change baseline; it could induce a two-fold increase in variability of growth in agriculture; and it would affect more severely the poor and certain parts of the country. The paper also finds that adaptation to climate change might cost an annual average of USD 0.8–2.8 billion; and an additional USD 1.2 to 5.8 billion if one takes into account residual damages which may not be addressed by adapting existing development plans. The paper also provides sector-specific insights on impacts and adaptation options in agriculture, road transport, and hydropower. In particular, rapid development of Ethiopia's hydro-potential, upgrading of the road design standards, and gradual diversification of the economy away from the more climate vulnerable sectors are likely to be important elements of any climate-resilient development strategy.

Keywords: Ethiopia, climate change, climate adaptation

1. INTRODUCTION

There is now widespread scientific consensus (IPCC 2007) that the global annual average temperature is likely to be 2°C above pre-industrial levels by 2050. A 2°C warmer world will experience more intense rainfall and more frequent and more intense droughts, floods, heat waves, and other extreme weather events. This will have dramatic implications for how countries manage their economies, care for their people, and design their development paths. Countries will need to adopt measures to adapt to climate change.

What is the plausible magnitude, timing, and sectoral distribution of damage? How expensive is adaptation likely to be? Building on a broader analytical effort (World Bank 2010a) undertaken recently for a larger set of countries, this paper explores these questions with respect to Ethiopia, a country which has experienced vibrant growth in recent years, but has historically been plagued by climate extremes (particularly droughts), resulting in large income swings; and is expected to be exposed to even more pronounced and frequent climate shocks in the future.

At the global level, studies to date have provided only a wide range of estimates of climate change impacts and adaptation costs, from USD 4 billion to USD 109 billion a year. A recent, more systematic analysis of adaptation actions across a range of sectors (World Bank 2010a), suggests a narrower cost range of USD 70–100 billion per year, with some USD 18 billion for Sub-Saharan Africa. At the country level, much of the existing literature addresses the analysis of impacts and adaptation either through a top-down approach, which provides economy-wide estimates of effects at coarse levels of spatial aggregation, with a resulting limited attention to the actual biophysical processes that turn climate shocks into sector-specific impacts. Other studies follow a sector-by-sector approach which fails to evaluate the indirect effects that climatic shocks on one sector might have on other ones, and on the economy as a whole.

This paper attempts to combine the two approaches. It undertakes a reasonably detailed analysis of how climate change might affect a selected number of priority sectors (agriculture, road infrastructures, and hydropower), and uses the findings to inform a general equilibrium evaluation of impacts and adaptation options. Both the sector-wise and the macro-economic analysis are conducted at suitable levels of spatial disaggregation (agroecological zones, river basins) to capture the relevant range of country specific variation of climate outcomes and bio-physical related responses (in terms of hydrology, plant and animal physiology, and man-made capital stock).

The study does not have the ambition to cover the full range of impacts that climate change might have on Ethiopia's economic and social development. Instead, it focuses on three sectors which play a strategic role in the country's current economic structure and in its future development prospects and are significantly exposed to current climate variability and future change. In particular:

- Agriculture, which accounted for 46 percent of Ethiopian GDP in 2006, is highly sensitive to seasonal variations in temperature and moisture;
- Roads, the backbone of the country's transport system, are often hit by large floods, which cause serious infrastructure damage and disruptions to supply chains;
- The dam infrastructure sub-sector—which provides hydropower and irrigation, and if suitably expanded can become an important source of foreign currency through energy exports—is affected by large precipitation swings.

While it is recognized that “soft” adaptation measures (such as institutional strengthening, community preparedness programs, watershed management, urban and rural zoning, and water pricing) have an important role to play, this paper focuses primarily on physical adaptation measures (sometimes referred to as “hard adaptation”), i.e. those that require an engineering response, and that tend to lend themselves more easily to a quantification of the costs of adoption.

The paper is structured as follows: the relevant country context is summarized in section 2; the methodology of analysis is described in section 3. Estimates of climate change impacts are presented in section 4, while the cost of adaptation strategies is analyzed in section 5. Section 6 draws policy implications and outlines areas for further inquiry.

2. COUNTRY CONTEXT

With around 85 million inhabitants, Ethiopia is the second most populated country in Sub-Saharan Africa (SSA) (World Bank 2011). Despite rapid economic growth over the past five years, per capita income—USD 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 of total merchandise exports in 2006/07, followed by oil seeds (15.8 percent), gold (8.2 percent), chat (7.8 percent), leather and leather goods (7.5 percent) and pulses (5.9 percent) (IMF 2008). Ethiopia is a net importer of wheat. All petrol, coal, and gas are imported.

Climate and Vulnerability to Climate Change

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 has traditionally been associated with three main climatic zones. These traditional agro-climatic zones are 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 zones were added at the extreme ends of the agro-climatic spectrum. These are Bereha (hot arid) and Wurch (cold and moist).

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 indicate a substantial rise in mean temperatures in Ethiopia over the 21st century and an increase in rainfall variability, with a rising frequency of both extreme flooding and droughts due to global warming. Given its large role in income and employment, agriculture also acts as a transmission chain of climate shocks towards other sectors of the economy.

Ethiopia is historically prone to extreme weather events. Rainfall in Ethiopia is highly erratic, and most rain falls in 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 localized famines, in addition to dozens of local droughts (Diao and Pratt 2007). Survey data show that between 1999 and 2004 more than half of all households in the country experienced at least one major drought shock (Dercon, Hoddinott, and Woldehanna 2005, cited in UNDP 2007). Major floods occurred in different parts of the country in 1988, 1993, 1994, 1995, 1996, and 2006 (ICPAC 2007).

Current Growth and Poverty Reduction Policies

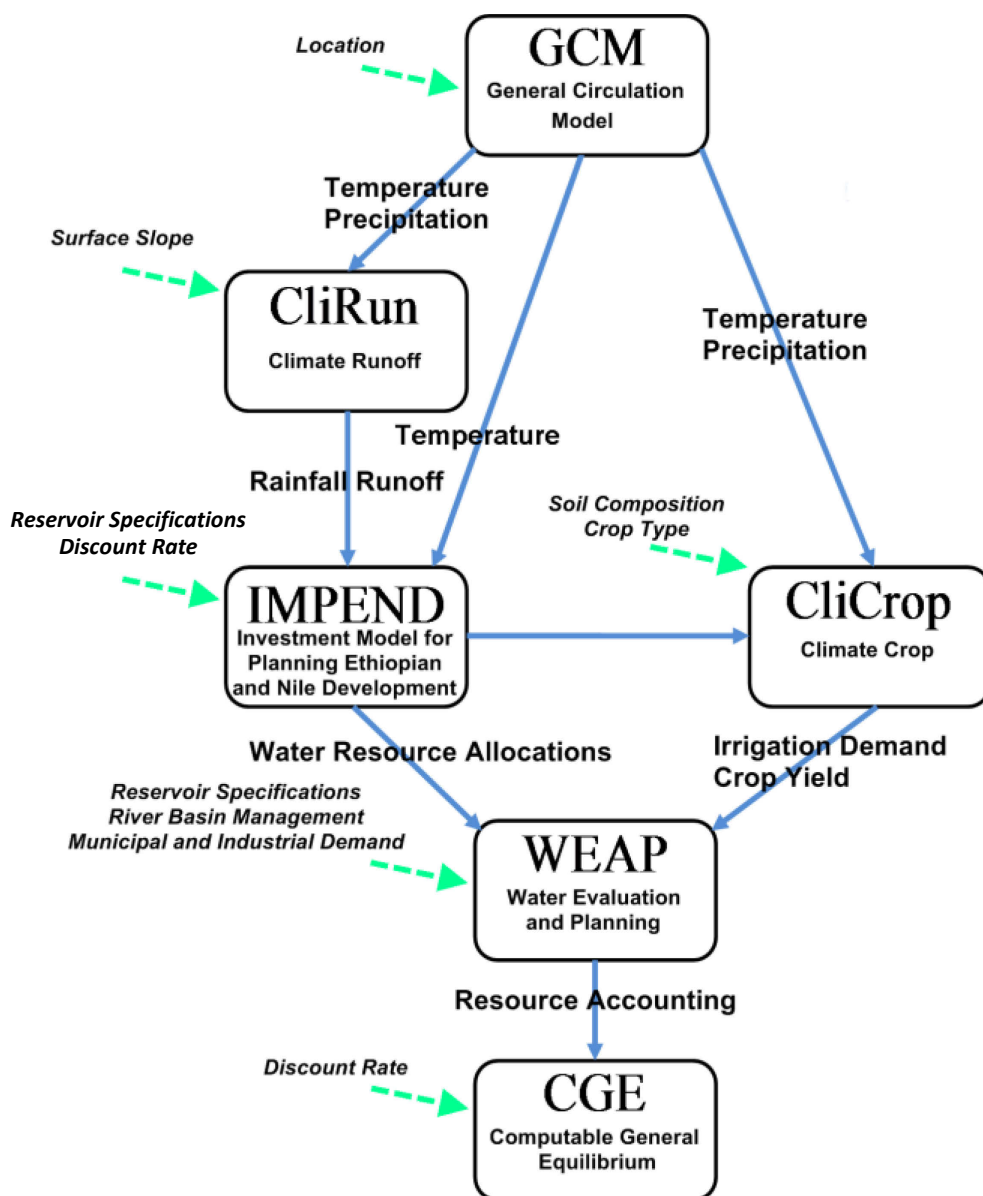
The Ethiopian government has prepared and adopted three successive poverty reduction strategy programs—the Sustainable Development and Poverty Reduction Program (SDPRP) (2002/03–2004/05), the 2005/06–2009/10 Plan for Accelerated and Sustained Development to End Poverty (PASDEP), and the current Growth and Transformation Plan (GTP) for 2010/11–2014/15. Policies related to 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, 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. Under the GTP, the agricultural sector is identified as a key driver of growth, and as this sector is particularly sensitive to climate changes, there is an opportunity to reflect on the implications of this analysis with respect to the GTP.

3. METHODOLOGY

This section summarizes the key elements of the methodology of analysis. Additional information on data, assumptions, and other elements of the analysis can be found in the background report to this research (World Bank 2010b). Climate change impacts and adaptation strategies were defined with regards to a baseline (no-climate change) development trajectory, designed as a plausible representation of how Ethiopia’s economy might evolve in the period 2010–2050, and reflecting historical trends and recent government plans and development strategies in selected sectors such as dams, hydropower development, irrigation, water management, and road building. Impacts are evaluated as the deviation of the variables of interest (economic welfare, sector development objectives, etc.) from the baseline trajectory. Adaptation is defined as a set of actions intended to reduce or eliminate the deviation from the baseline development path caused by climate change.

The impacts of climate change and the merits of adaptation strategies depend on future climate outcomes, which are typically derived from Global Circulation Models (GCMs), and are uncertain, both because the processes are inherently stochastic and because the GCM models differ in how they represent those processes. The overall approach of the paper is to link a dynamic multisectoral and multiregional Computable General Equilibrium model (CGE) with a range of sectoral climate change impact models that generate quantitative estimates of effects on water systems, agriculture, hydro-energy, and road transport infrastructure (Figure 3.1).

Figure 3.1—Flow chart of model sequencing



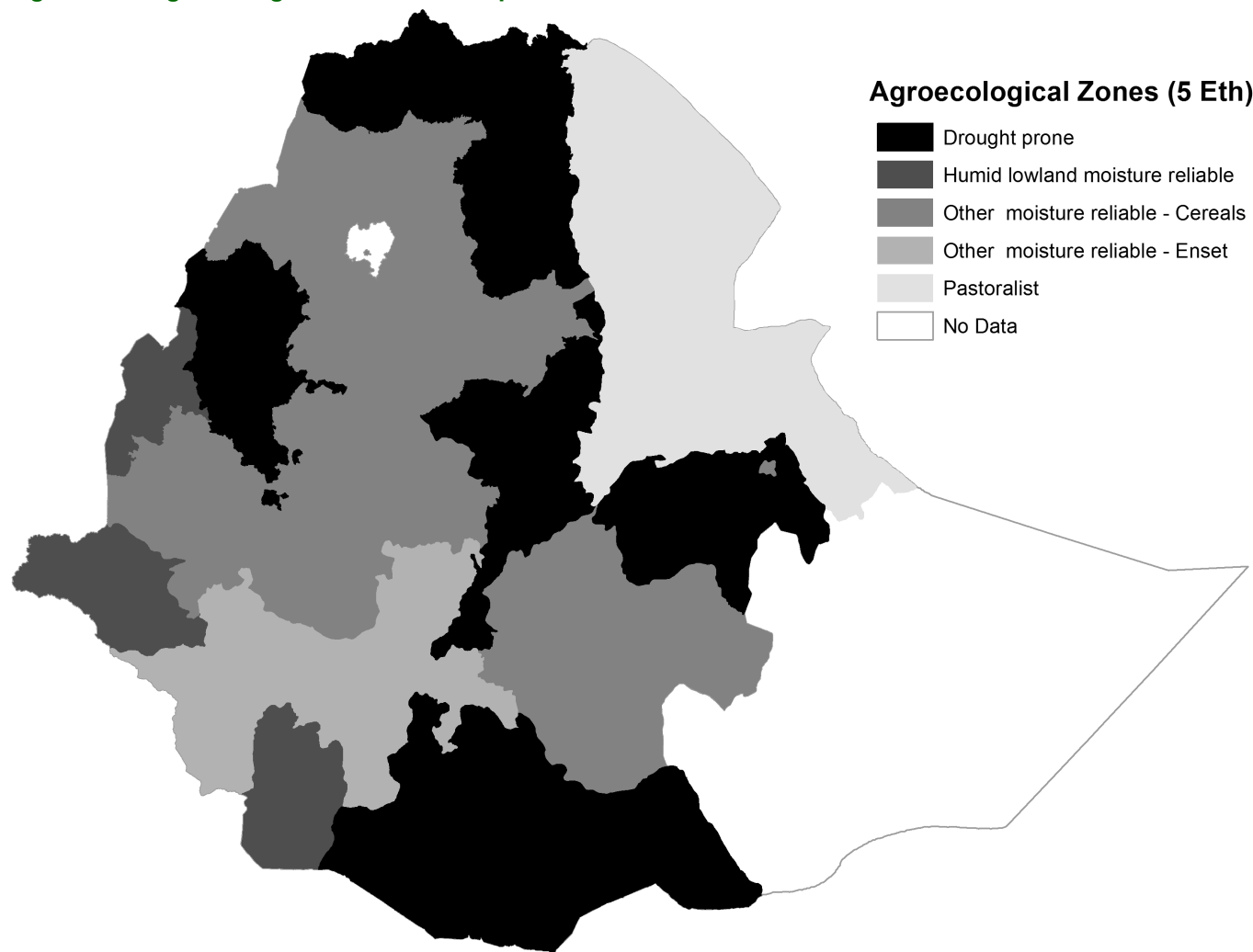
Source: Authors' compilation.

Global circulation models (GCMs) lie at the beginning of the modeling chain. These models take as inputs quantities of greenhouse gases emitted and produce climate outcomes through time and across space as a function of these emissions and initial conditions. A series of hydrological and crop models are the next elements in the chain. These models take climate outcomes and convert them to biophysical processes on the ground. Outcomes of particular interest are crop yields, which temperature and rainfall can influence substantially, and hydrological flows within river basins, including the incidence of floods.

The flow of information through the integrated river basin and water resource model is generally linear, as shown above in Figure 3.1. Climate data are put into CliRun and CliCrop in order to produce stream flow runoff estimates and crop irrigation demand estimates respectively. CliRun is a two-layer, one-dimensional infiltration and runoff estimation tool that uses historic runoff as a means to estimate soil characteristics. A 0.5° by 0.5° historic global runoff database generated by the Global Runoff Data Center (GRDC) and measured historic runoff is used to calibrate CliRun. CliCrop is a generic crop model that simulates crop yields and soil water, as described in section 3.1.

Inflows calculated using CliRun are passed to the Investment Model for Planning Ethiopian Nile Development (IMPEND) in which reservoir storage capacity, hydropower capacity, and irrigation developments are optimized to maximize net benefits (Block and Strzeppek 2010). The outputs from IMPEND, along with the irrigation demands estimated from CliCrop, are then passed to the Water Evaluation and Planning System (WEAP – Sieber and Purkey 2007) where water storage and hydropower potential are modeled based on their interaction with the climate and socio-economics of the river basins being modeled. The analysis is spatially explicit, using as units of inquiry the country’s five agroecological zones (Figure 3.2) in some cases; and in others, river basins.

Figure 3.2—Agroecological zones in Ethiopia



Source: Dorosh and Thurlow (2009).

Approach to Future Climate Uncertainty

Climate inputs specific to Ethiopia and its river basins, both historic and future, such as monthly temperature and precipitation, are used to drive the river basin and water resource model and crop models mentioned above. Models are calibrated using historical data from the Climate Research Unit (CRU) on global monthly precipitation and temperature; information on future climate has been taken from four GCMs, forced with different CO₂ emission scenarios to represent the total range of climate changes facing Ethiopia in 2050 as defined by the change in Climate Moisture Index (CMI)¹. There were four climate change scenarios used for this analysis. Two scenarios—the Dry 1 and Wet 1—are the globally wettest and driest scenarios. These scenarios were included to enable comparison with global analysis of adaptation costs (World Bank 2010a). The Dry 2 and Wet 2 scenarios define the maximum range of CMI change only over the area of Ethiopia (Table 3.1). They result from the combination of three Special Report on Emissions Scenarios (SRES) and 22 climate models developed for the fourth IPCC assessment (AR4). The Dry 2 scenario shows reductions in average annual rainfall over 2045–2055 in Ethiopia greater than 15 percent. The Wet 2 scenario shows increases in average annual rainfall in Ethiopia close to 25 percent.

Table 3.1—Global circulation model scenarios for Ethiopia country track study

Scenario	GCM	SRES	CMI Development
Wet 1: “Global Wet”	ncar_ccsm3_0	A2	10%
Dry 1: “Global Dry”	csiro_mk3_0	A2	-5%
Wet 2: “Ethiopia Wet”	ncar_pcm1	A1b	+23%
Dry 2: “Ethiopia Dry”	ipsl_cm4	B1	-15%

Source: Authors' compilation.

Notes: GCM= Global Circulation Model; SRES= Special Report on Emissions Scenarios; CMI= Climate Moisture Index.

3.1. Crops, Livestock, and Drought Modeling

CliCrop was used to measure climate change impacts on water stress and examine field level adaptation options including mulching and water harvesting. The output of CliCrop is used as input to the Computable General Equilibrium Model (CGE, section 3.3) as shocks/stressors caused by the predicted monthly changes from the GCMs. The output of CliCrop is also used in the WEAP analysis of changes in irrigation demand and in reservoir water supply (section 3.2).

Livestock Model

This paper evaluates the effect of changing climate conditions on livestock productivity, relying on a hybrid approach that has two components: a “biophysical” component that considers the effect of temperature on expected livestock incomes, and a “feed” component that incorporates the effect of changing availability of livestock feed using the outputs of CliCrop². The biophysical component relies on the results of a structural Ricardian model of African livestock developed by Seo and Mendelsohn (2006)³. This model analyzes the interaction between temperature and livestock and considers the adaptive responses of farmers by evaluating which species are selected, the number of animals per farm, and the net revenue per animal under changes in climate.

Although the direct effects of heat stress on livestock have not been studied extensively, warming is expected to alter the feed intake, mortality, growth, reproduction, maintenance, and production of animals. Collectively, these effects are expected to have a negative impact on livestock productivity (Thornton et al. 2009).

¹ The Climate Moisture Index (CMI) depends on average annual precipitation and average annual potential evapotranspiration (PET). If PET is greater than precipitation, the climate is considered to be dry whereas if precipitation is greater than PET, the climate is moist. Calculated as $CMI = (P/PET) - 1$ {when $PET > P$ } and $CMI = 1 - (PET/P)$ {when $P > PET$ }, a CMI of -1 is very arid and a CMI of $+1$ is very humid. As a ratio of two depth measurements, CMI is dimensionless. Average annual PET is a parameter that reflects the amount of water lost via evaporation or transpiration (water consumed by vegetation) during a typical year for a given area if sufficient water were available at all times. Average annual evapotranspiration (ET) is a measure of the amount of water lost to the atmosphere from the surface of soils and plants through the combined processes of evaporation and transpiration during the year (measured in mm/year). ET, which is both connected to and limited by the physical environment, is a measure that quantifies the available water in a region. Potential evapotranspiration is a calculated parameter that represents the maximum rate of ET possible for an area completely covered by vegetation with adequate moisture available at all times. PET is dependent on several variables including temperature, humidity, solar radiation, and wind velocity. If ample water is available, ET should be equal to PET.

² Ideally, a livestock process model would be available that was capable of explicitly analyzing the effect of changing climate conditions on livestock productivity, and the resulting adaptive responses of livestock farmers. Because no such model is publicly available, this analysis relies on the hybrid approach described above.

³ The Ricardian approach examines how crop production varies in regions of different climates and then infers the effect of climate from these differences (Mendelsohn, Nordhaus, and Shaw 1994). The approach explicitly embeds farm adaptations as found in the pooled (time series and cross sectional) data. Using these data, it is possible to forecast how climate changes affect profits and production in future years.

Drought Model

Periodic drought in Ethiopia causes severe reductions in food availability, causing government expenditures on food aid and emergency drought relief to swell during these periods. In recent years, the Ethiopian government has maintained records of expenditures on vulnerability and food security (VFS), which have typically increased during extreme droughts (e.g., 1999–2000 and 2003–2004). Using a reduced form statistical model, this paper estimates the relationship between climate drivers and Ethiopian VFS expenditures, and develops nationwide projections of those expenditures from 2001 to 2050 under the base and four climate scenarios. The reduced form statistical model relies on historical expenditure data on VFS, historical climate data in drought-prone regions, and a dummy variable reflecting a significant increase in VFS funding from 2001/02 forward because of a federal special purpose grant for food security (World Bank 2008). The latter variable is included in the statistical formulation to explain this large surge in expenditures on VFS.

3.2. Road Transport

The stressor–response methodology used in this paper is based on the concept that exogenous factors, or stressors, have a direct effect on materials used in road infrastructures, and trigger their subsequent response (Chinowsky et al. 2011; Chinowsky and Arndt. 2012). Two primary climate stressors were included in the analysis: temperature and precipitation. The stressor–response factors used in the analysis are divided into two general categories: impacts on new construction costs, and impacts on maintenance costs. To determine the costs of climate change impact, two different elements are considered: costs to maintain existing roads, and costs to adapt roads by improving them structurally at regular design life intervals. Cost estimates were derived from both commercial cost databases and from country-specific information (where available).

The development of annual cost estimates for the flooding impacts on road capital stock combines lifecycle concerns and climate impacts. Road and highway flood losses were calculated based on monthly runoff estimates generated from CliRun simulations. While road and highway damages actually occur under flooding conditions over a range of sub-monthly time scales (i.e. hourly, daily, weekly, etc.), only monthly GCM data were available for this analysis. A custom damage function was used to generate loss estimates based on the return period of precipitation intensities. The function used results from adjusting a general damage function for flooding impacts on roads, taking into account current design standards and engineering judgment. The effect of climate change on the curve is expressed in terms of changes in frequency and intensity of floods; for example, a 70-year flood in the baseline may occur more frequently, e.g. it might become a 50-year flood under climate change.

3.3. Hydropower and Water Resources

Hydropower simulation was done using a hydro power planning model developed for Ethiopia: the IMPEND model (*Investment Model for Planning Ethiopian Nile Development*) (Block and Strzepek 2010). IMPEND was developed to plan reservoirs and power generation facilities on the Upper Blue Nile River in Ethiopia. The analysis does not purport to inform project-level decisions; but rather to estimate:

- 1) Climate change impacts on annual power production up to 2050, as an input to the CGE model described in section 3.3
- 2) The cost to restore the hydropower generation to levels attainable in the no-climate change scenario, by constructing additional hydropower capacity.

Integrated River Basin Analysis

A water planning model—WEAP (Sieber and Purkey 2007), a software tool for integrated water resources planning—is used to evaluate the potential interactions between growing demand from the municipal and industrial (M&I), irrigation, and hydropower sectors under the baseline and climate change. The model evaluates these intersectoral effects between 2001 and 2050, and generates time series of impacts on irrigated agricultural yields and on hydropower generation under each of the climate scenarios. These time series are used as perturbations to irrigation yields and hydropower generation estimates in the CGE under each of the climate scenarios.

By modeling surface water availability (runoff), reservoir storage, and demand from different sectors, the model permits investigation of intersectoral conflicts between water demands. Municipal and industrial (M&I) and irrigation demands are projected based on World Bank and in-country sources; hydropower production is calculated for existing and planned dams based on an expected investment and construction schedule. The withdrawals and hydropower production estimates were validated with historical values.

3.4. Macro-Economic Analysis

The economic impact of climate change is simulated using a dynamic computable general equilibrium (CGE) model. The CGE model simulates the operation of commodity and factor markets across the economy. It provides a “simulation laboratory” for analyzing the direct and indirect impacts of different climate change and adaptation investment scenarios.

The model specifies that producers maximize profits under constant returns to scale production technologies, with the choice between factors governed by a constant elasticity of substitution (CES) function for primary factors and fixed input–output coefficients for intermediate inputs. Producers choose to supply to domestic or world markets assuming a constant elasticity of transformation (CET) function that distinguishes between exported and domestic-market goods. Profit maximization drives producers to sell in markets where they can achieve the highest returns, based on domestic and export prices. Similarly, imports are assumed to be imperfect substitutes for domestic goods (the “Armington” assumption). Additional assumptions include:

- 1) Ethiopia faces fixed prices on world markets (the “small country” assumption).
- 2) Aggregate government expenditure and aggregate investment are assumed to be fixed shares of aggregate absorption.
- 3) Savings rates are adjusted to finance investment, achieving savings-investment balance.
- 4) A flexible exchange rate adjusts in order to maintain a fixed level of foreign savings.
- 5) Labor is fully employed and mobile across sectors.

The model distinguishes among various institutions that receive income and pay taxes, including:

- Enterprises receive profit income, pay direct taxes, pay income to households in form of dividends, and save.
- Five rural and five urban representative household groups, comprising “poor” and “non-poor” households receive factor income and transfers, pay direct taxes, consume commodities, and save.
- Government receives revenues from activity taxes, sales taxes, direct taxes, and import tariffs, and makes transfers to households, enterprises and the rest of the world, purchases commodities (government consumption expenditure), and saves.

This model is calibrated to a social accounting matrix (SAM) for the year 2005/06 (EDRI 2009). The SAM provides a detailed representation of the structure of production, demand, international trade, and income distribution and contains a regional disaggregation of agricultural activities, household income, and household consumption. The five regions distinguished in this database are differentiated by their agroecological characteristics (humid lowlands moisture reliable; moisture sufficient highlands—cereals based; moisture sufficient highlands—enset based; drought prone highlands; pastoralist arid lowland plains). The model contains 22 commodity groups and 46 activities including 35 regionally differentiated agricultural sectors. Fifteen primary factors of production are identified: four types of labor, agricultural land and livestock capital in each of the five agroecological zones, and non-agricultural capital employed in industry and the service sector.

4. IMPACTS

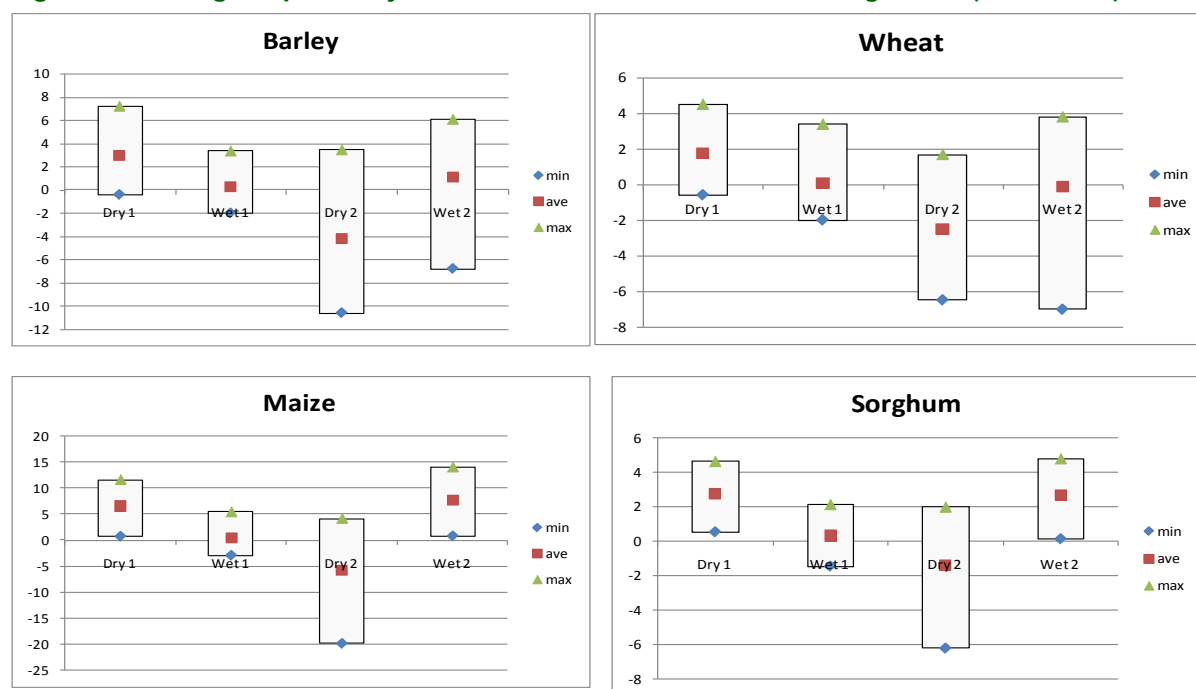
4.1. Agriculture

4.1.1. Impacts on Crops

With the use of CliCrop, the changes in CO₂ concentration, precipitation, and temperature from the four GCMs are used to estimate the changes in production (yield) each year for the major crops grown in Ethiopia. Changes in yields are due to either the lack of available water (dry years), or due to the overabundance of water (wet years) that causes waterlogging. Regional and temporal trends over the four scenarios are depicted below in Figure 4.1.

Climate impacts appear to be significant, but variable over regions and crop type. The magnitude of these impacts tends to grow stronger with time. The Dry 2 scenario is the most damaging scenario due to the frequent occurrence of droughts. The impacts of climate on yields are first-order effects that trigger direct and indirect economic impacts such as reductions in income, employment, savings, and investments. These impacts are captured in the CGE analysis.

Figure 4.1—Range of percent yield deviations from no-climate change base (2006–2050) for selected crops



Source: Authors' compilation.

CO₂ fertilization is included in the analysis but is found not to make a significant difference. This is consistent with recent research that suggests that CO₂ fertilization effects are likely to be considerably smaller than initially thought.

4.1.2. Impacts on Livestock

The analysis developed two sets of time series, related to the “income” and the “feed” effect described in section 3.1. Under the Ethiopia wet and the two global scenarios, income in each agroecological zone (AEZ) falls to 70 to 80 percent of baseline levels. Under the more pronounced temperature effects of the dry scenario, livestock incomes fall to roughly 60 percent of mean baseline levels, although in the moisture reliable humid lowland zone they reach a low of roughly 55 percent.

Livestock productivity is affected most severely under the Ethiopia dry scenario, in which the ratio between future and baseline productivity falls to a low value of approximately 0.70 in the moisture reliable humid lowland zone, or a 30 percent decline in productivity. Under each scenario, there is a downward trend in productivity over the 2001 to 2050 period.

4.1.3. Drought Expenditures

The average annual projected expenditure on droughts—the expenditures on vulnerability and food security (VFS) described earlier—varies from a low of USD 7.3 million annually under the Ethiopia wet scenario in the 2040s to a high of USD 1.2 billion in the Ethiopia dry scenario in the 2030s. This compares to average annual recurrent drought expenditure between 1997/98 and 2005/06 of roughly USD 696 million and a maximum annual expenditure of USD 1.8 billion.

4.2. Road transport

Table 4.1 summarizes the finding of the analysis of climate change impacts on road infrastructure, which includes impacts on maintenance and impacts related to flood events. As for first type of effects, based on the existing road inventory and plans for network expansion, it is estimated that maintenance on paved roads that is directly attributable to climate change ranges from USD 5 million to USD 13 million per year depending on the climate model used for the projection. The increased maintenance cost for unpaved roads is estimated between USD 2 million and USD 14 million per year depending on the climate model used.

In addition to increasing regular maintenance, climate change is likely to cause more frequent and severe flood events, which require additional repair investment to bring the affected roads back to functioning order. This second type of impacts is estimated to be much larger than the first, with an average annual cost in the range of USD 250 million to USD 340 million.

Table 4.1—Summary of impacts costs on roads (annual average, 2010 – 2050, USD million)

	Wet 2	Dry 2	Wet 1	Dry 1
Impacts on regular maintenance	31.45	21.12	14.84	20.14
Flood impacts	340.86	296.92	265.70	257.73
Total impacts costs	372.31	318.04	280.54	277.87

Source: Authors' calculations.

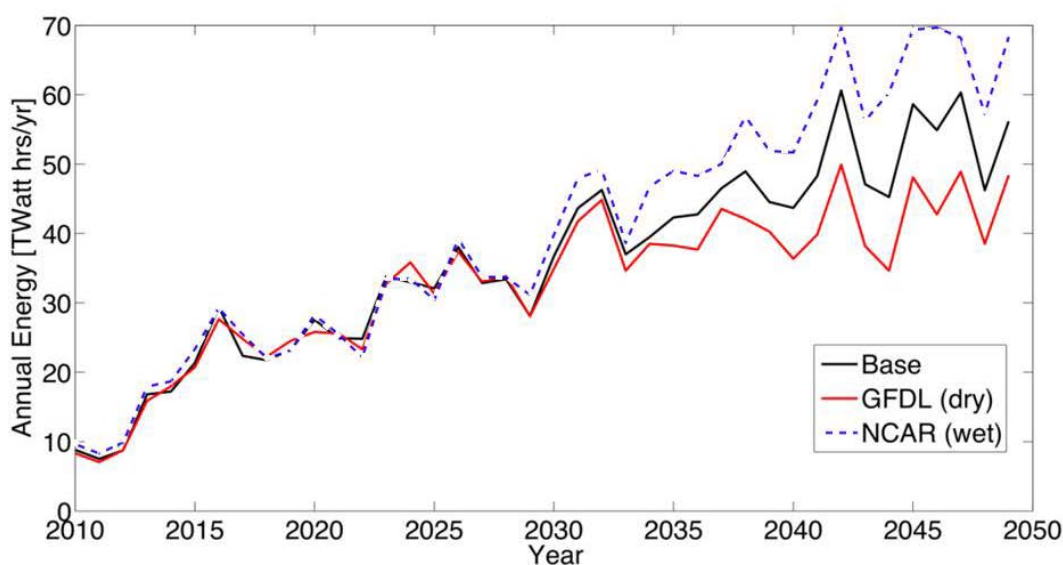
4.3. Water Resources and Hydropower

4.3.1. Impacts on Hydropower

The IMPEND model provides an estimate of the potential change in hydropower generation capability. The results of a comparison between the base, Ethiopian dry, and Ethiopian wet scenarios are shown below in Figure 4.2.

As the figure shows, climate change does not change the variability of hydropower generation but impacts the mean annual energy generation. The wet scenario produces more hydropower than the base, and the dry scenario produces less than the base. However, the deviations from the base only start after 23 years because initially there is so little installed hydro capacity that changes in flows have no impact. This is an important result as it shows that over the next couple of decades climate change is likely to have negligible effects on decision making in the hydropower sector. But after 2030, Ethiopia has a chance to gain or lose from climate change. This suggests the need for a careful risk-based approach to hydropower investments after 2030, which accounts for close to half the value of the projects currently included in the government's sector investment program.

Figure 4.2—Hydropower generation 2008–2050 under two change scenarios



Source: Authors' compilation.

Notes: GFDL = Geophysical Fluid Dynamics Laboratory scenario; NCAR = National Center for Atmospheric Research scenario.

4.3.2. Intersectoral Competition for Water

The WEAP analysis first establishes the baseline (i.e., no climate change) projections through 2050 for key water demands, including municipal and industrial (M&I), hydropower, and irrigation (obtained from CliCrop modeling). Next, it analyzes baseline competition among water end-users given baseline water availability; that is, competition for water that would take place even in the absence of climate change. Specifically, the impacts of the competition are measured in terms of reduced hydropower production and irrigated crop yields relative to maximum potential generation and yields. In addition, the analysis evaluates the effects of these rising demand on water flows from Ethiopia into other countries. Finally, the analysis incorporates the runoff under the climate change scenarios to see if competition among end-users intensifies or otherwise changes, as well as how flows from Ethiopia to other countries are affected.

The hydropower and irrigation results are used to produce adjustments in the hydropower and crop impact results generated by IMPEND and the crop models under both baseline and climate change. Both of the other models consider climate change effects, but no intersectoral effects.

The analysis assumes increasing M&I demands, increasing irrigation to 3.7 million ha by 2050, full expansion of hydropower to levels outlined by the Ministry of Water Resources' Water Sector Development Plan (MWR 2002), and no transboundary flow requirements⁴. The result and assumptions of the analysis of competition under both baseline and climate change are described below.

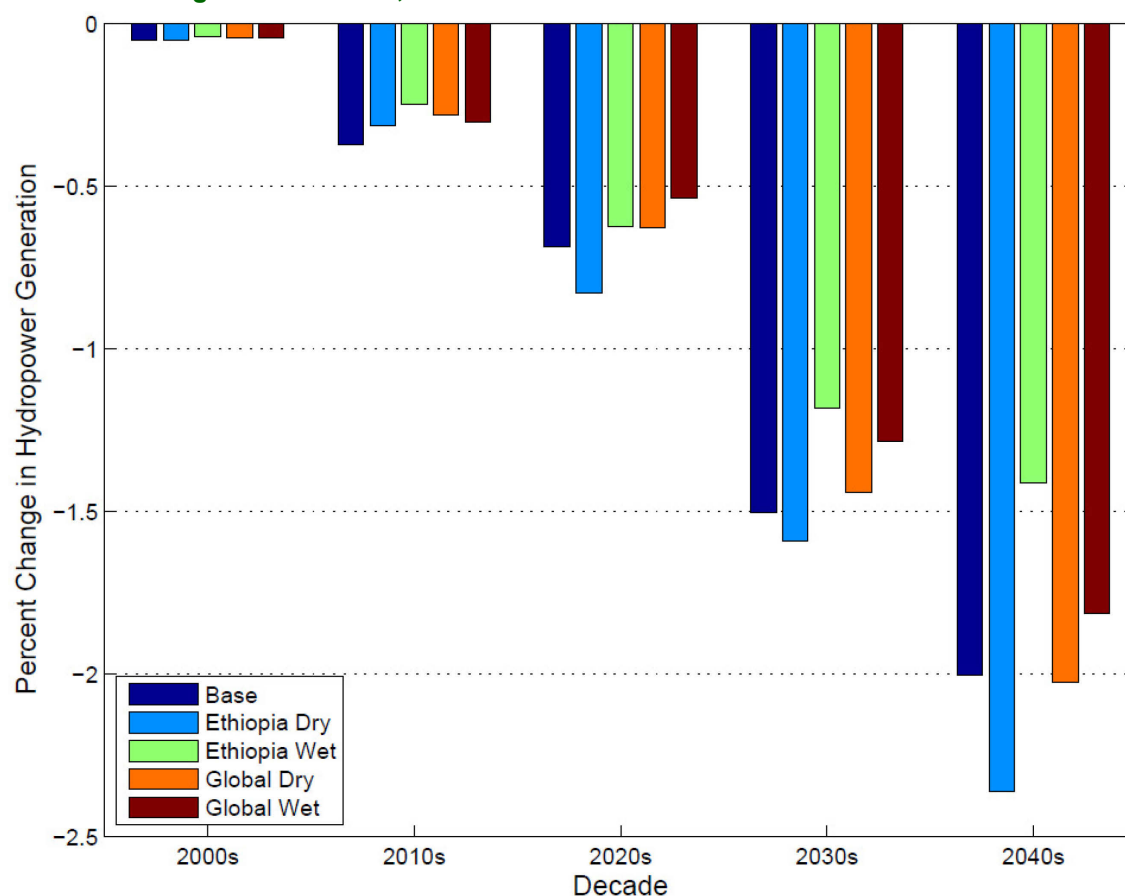
4.3.3. Intersectoral Effects on Hydropower Production

Assuming that under water scarcity, resources would be allocated with first priority to municipal and industrial demands, followed by irrigation, with hydropower having access to the residual volume of water, the analysis evaluated effects on hydropower production (as estimated by the IMPEND model) in the baseline, and under four climate change scenarios.

Baseline hydropower production over the 50-year period is 1.89 billion MWH. As expected, under the Ethiopia wet scenario outputs are highest (13.6 percent higher than baseline), and under the Ethiopia dry scenario outputs are lowest (8.7 percent lower than baseline). The two global scenarios hover much more closely to the baseline (dry is 2.2 percent higher and wet is 9.3 percent higher than baseline).

Figure 4.3 presents the mean decadal reductions in hydropower production given increased M&I and irrigation demands through 2050. Changes in hydropower production occur because the higher-priority downstream irrigation and M&I demands affect the reservoir water release schedules and thus cause suboptimal production conditions. For example, if irrigation demand causes water to be released in May rather than stored to increase hydraulic head, overall power production can decline.

Figure 4.3—Mean decadal changes in hydropower production given increasing municipal and industrial demands and irrigation demands, relative to a no-demand scenario



Source: Authors' compilation.

⁴ This analysis was unable to evaluate the water resources implications of the existing Nile Basin treaty, so does not impose transboundary flow requirements. Instead, the analysis evaluates the implications of rising domestic demand for transboundary water flows from Ethiopia to other countries.

The maximum effect is under the Ethiopia dry scenario, where an average decadal effect for the 2040s reaches -2.5 percent. The findings of the analysis in terms of total volume of power produced (millions of MWH) are presented in Table 4.2.

Table 4.2—Total hydropower production under different demand and climate scenarios (million MWH, 2010 – 2040)

Demand scenario	Baseline (no climate Change)	Wet 2	Dry 2
No competing demand to be met	1,884	2,136	1,722
Demand for M&I to be met	1,881	2,133	1,718
Demand for M&I and for irrigation to be met	1,858	2,113	1,696

Source: Authors' calculations.

Note: M&I=municipal and industrial.

4.3.4. Changes in Irrigation Water Availability and Crop Yields

Intersectoral water conflicts will also impact the availability of water for irrigation, which will decrease crop yields in irrigated areas. Based on communication with the Ministry of Water Resources, irrigated agriculture will expand considerably by 2050 from 1.6 percent to 35 percent (3.7 million ha) of the approximately 10 million ha of agricultural land in Ethiopia (total agricultural area is assumed to remain relatively constant). WEAP generates unmet demand estimates based on a balancing of demands in the system. These unmet irrigation demands (all M&I demands are met because it has top priority for water use) are produced for each basin and summed across basins to generate percent reductions in irrigation water availability between 2001 and 2050 under the baseline and each of the climate scenarios. Table 4.3 illustrates these unmet irrigation water demands, which rise to an annual average of up to 965 million m³ under the Ethiopia dry scenario in the 2040s.

Table 4.3—Unmet demand for irrigation (million m³, annual average by decade)

Scenario	2010	2020	2030	2040
Baseline	3.98	23.00	135.00	443.00
Wet 2	0.00	9.63	61.90	160.00
Dry 2	8.33	122.00	496.00	965.00

Source: Authors' calculations.

4.4. Economy-Wide Impacts

4.4.1. Baseline

The CGE analysis specifies a “baseline” path to 2050 that reflects development trends, policies, and priorities in the absence of climate change, but incorporates an historical pattern of climate shocks. The baseline provides a reasonable trajectory for growth and structural change of the economy in the absence of climate change that can be used as a basis for comparison with various climate change scenarios.

The decisions of consumers, producers, and investors change in response to changes in economic conditions, which are affected by different sets of climate outcomes. The model allows a degree of endogenous adaptation within periods, with changes in labor allocation across sectors and crops in response to shocks.

In the baseline, underlying rates of productivity growth, world prices, foreign aid inflows, tax rates, and government investment policies are imposed exogenously. In the climate change scenarios, climate shocks affect various parameters and exogenous variables. By comparing results from the baseline path with those from the climate change scenarios, the CGE model provides an estimate of the economy wide impact of climate change.

Because comparisons are made with specific changes imposed and everything else held constant, the interesting results—the differences in outcomes between an experiment and the baseline—are generally insensitive to changes in the assumptions underlying the baseline. Results are generally more sensitive to the trajectory of baseline variables that are also policy variables. In the adaptation section, potential strategic options for adapting to climate change are presented.

The scenarios considered are described in Table 4.4. A “Base” scenario provides the baseline with historical climate shocks, using monthly historical data from the past fifty years, extended over the future period. The climate scenarios involve shocks to: (1) agricultural productivity by crop and region, (2) hydro-electric power production, (3) flood damage by region to roads, crop yields, and livestock.

Table 4.4—Scenarios used in the CGE analysis

Name	GCM	CMI	Description
Base	Historical climate		Historical climate shocks
Wet 2	Ncar_ccsm3_0-sresa1b	23%	Very wet climate change shocks for Ethiopia
Wet 1	Ncar_ccsm3_0-sresa2	10%	Global wet climate change shocks
Dry 1	Csiro_mk3_0-sresa2	-5%	Global dry climate change shocks
Dry 2	Gfdl_cm2_1-sresa1b	-15%	Very dry climate change shocks for Ethiopia

Source: Authors' compilation.

Notes: GCM=Global Climate Model; CMI=Crop moisture index change.

4.4.2. Economic Impacts

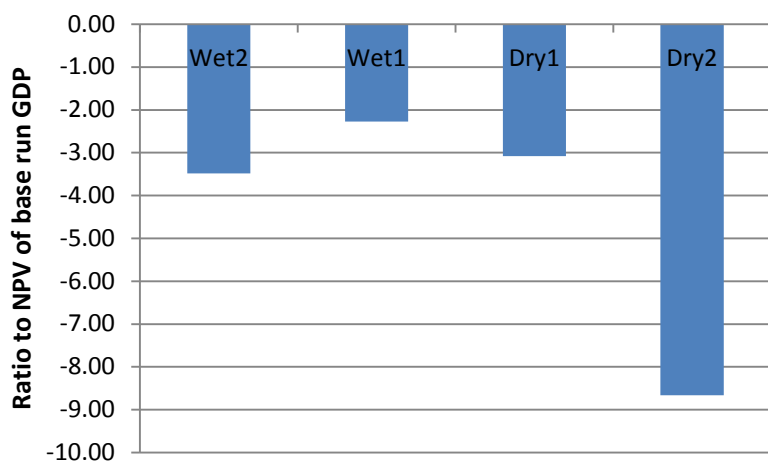
Climate change is expected to influence the growth and development of Ethiopia through four main transmission mechanisms:

- 1) **Productivity changes in dry land agriculture.** The CGE model determines how much land, labor, capital, and intermediate inputs are allocated to a crop, as well as an estimated level of production under the assumption of normal climatic conditions.
- 2) **Water availability.** Based on the river basin models, the CGE model incorporates directly the fluctuations in hydropower production due to variation in river flow, which are exogenous in the model.
- 3) **Road Infrastructure maintenance and upkeep** are influenced by changes in temperature and precipitation. In the CGE model, these greater maintenance costs result in either less rapid expansion in the road network for a given level of spending on roads or an actual shrinkage in the network if the resources necessary to maintain the network are unavailable.
- 4) **Extreme events**, such as floods and extended droughts, may become more frequent under climate change. The GCM simulations take flood damage to crops, livestock, and road infrastructure into account.

The CGE model captures accumulation processes such as physical capital and human capital, growth in technology as well as necessary institutional frameworks, which largely drive economic growth. To the extent that climate change reduces agricultural or hydropower output in a given year, it also reduces income and hence savings. This translates into reduced investment, which translates into reduced production potential in the future. Generally, even small differences in rates of accumulation can lead to large differences in economic outcomes over long time periods. The CGE model is well positioned to capture these effects. The key findings of the CGE analysis are summarized below.

Climate change has significant negative impacts on welfare. The Dry 2 and Wet 2 scenarios are the most damaging in net present value (NPV) terms. The Wet 2 scenario is especially damaging in the final decade due to extreme floods, with GDP loss of nearly 8 percent compared to the base. Under the Dry 2 scenario, where the damage is larger and is spread more evenly over the period, by 2050 GDP is projected to be some 10 percent smaller than in the no-climate change baseline (Figure 4.4).

Figure 4.4—Welfare loss from climate change scenarios

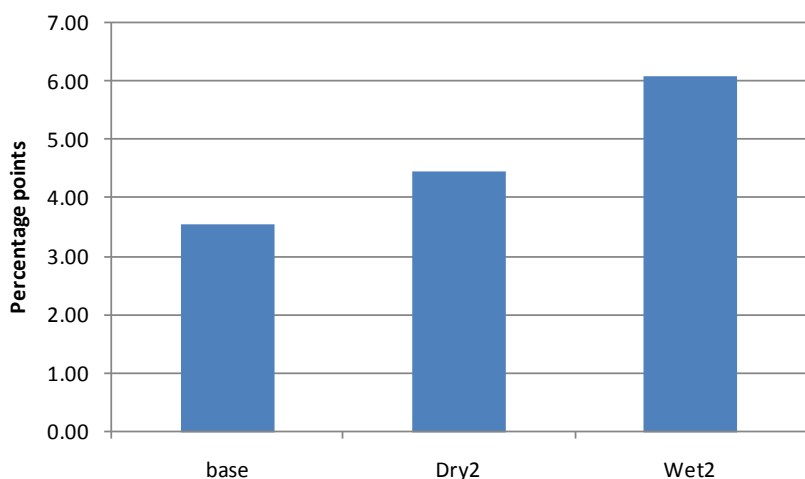


Source: Authors' compilation.

Notes: Difference in Net Present Value (NPV) of total absorption (defined as GDP plus imports, minus exports) from the base run as a percent of NPV of base GDP. All figures are calculated over the 2010–2050 time horizon.

Climate change increases variability in agriculture income. The variance in yields seems to increase with time, and the shocks become more negative, which is consistent with the view that the climate change shocks will become more intense and damaging over time, as demonstrated in Figure 4.5.

Figure 4.5—Standard deviation of agricultural year-to-year growth rates



Source: Authors' compilation.

Notes: Standard deviation (SD) of annual growth rates of agricultural GDP for the different scenarios over the entire period.

The wet scenarios tend to be better for crop yields than dry scenarios, but floods are damaging, especially in the final decade. The impacts of climate change shocks differ greatly across regions for different scenarios. In the pastoral arid lowland (one of the five agroecological zones), agriculture is almost exclusively based on livestock, and is very sensitive to water availability and temperature.

The **impacts of the shocks on electricity generation** are significant. However, when we account for the construction of new dams, the supply of electricity grows faster than domestic demand and there are significant exports within a few years. The climate change shock scenarios lead to large variations in exports, but in no scenario is there a significant shortage or price rise in the domestic market.

Climate change impacts tend to hurt the poor more. In general, the poor suffer slightly less in terms of means, but have to adjust to more variability in income and hence aggregate consumption than non-poor households.

5. ADAPTATION

This section identifies a set of adaptation measures in agriculture, roads, and hydropower. The following menu of adaptation options is considered:

- 1) Increase irrigated area.
- 2) Increase research and development for agriculture.
- 3) Modify plans for expansion of hydroelectric power (volume or timing of investment).
- 4) Build climate resistant road infrastructure (e.g., increase the capacity of roads and bridges to withstand greater heat and precipitation).

By and large, these options are identified by taking as given certain sector development objectives (e.g. the road network expansion plan; or the target production of electricity from hydropower), and defining ways to achieve those objectives even under varying climate conditions. More generally, however, adaptation might also involve changing the sector development plans, or promoting different allocation of resources across sectors. An illustrative investigation of this different line of reasoning is summarized in section 5.5. below.

5.1. Agriculture

Taking into account the Government's recent development activities in the sector, as well as the significant (and yet largely untapped) potential for irrigation growth, this paper proposes a "portfolio strategy" approach to adaptation in agriculture. Such an approach combines, on the one hand programs in Research and Development (R&D) and farm management practices aimed primarily at boosting yields in rainfed areas; and, on the other, investments in irrigation and drainage infrastructure. The proposed approach is consistent with recent work on adaptation in agriculture at the global level (Nelson et al. 2009), which analyzed R&D and irrigation/drainage as a direct adaptation strategy; and the expansion of rural roads as an indirect strategy.

The two pillars of the adaptation approach analyzed here (R&D and irrigation/drainage) are meant to capture key aspects of a strategy capable of tackling the essential features of the climate of the future: i.e., an increase in temperature (common to all scenarios); and changes in precipitation patterns (in varying directions and magnitudes, depending on the climate change scenarios).

Temperature increases under all scenarios, with negative impacts on crops yields. Investment in R&D is thus intended to maintain the technology-induced productivity growth in the agricultural sector at the base, no-climate change rate by developing new crop varieties optimized for the changed climate. In each scenario, an initial period of extensive R&D activities over the first ten years was assumed to allow time to learn what direction climate change was taking for Ethiopia. This would allow infrastructure designs to minimize the risk of "regrets" associated with the selection of the "wrong" adaptation response.

In all four adaptation scenarios, the baseline irrigation development plan of 3.7 million hectares by 2050 is increased gradually to 4.1 million by 2050. The level of irrigation infrastructure is matched to the magnitude of climate change induced irrigation deficit. Note that it is possible to have increases in irrigation deficit even in wet scenarios. As warming increases, crops demand an amount of water greater than the increases in precipitation during the growing season. Changes in precipitation intensity and seasonality call for increased installation of drainage systems especially in wet scenarios.

The order of magnitude of investments in agriculture adaptation was determined by taking into account the opportunity cost of diverting resources from other sectors. Using CGE modeling, an average annual cost of about USD 70 million was assessed by expert judgment to be in a reasonable range so as to avoid an excessive drain on economy-wide growth⁵.

Irrigation infrastructure is installed on 400,000 hectares for all scenarios. However, for the Wet 2 scenario the design was for only stream diversion for supplemental irrigation. For the Wet 1 scenario, again only stream diversion was considered, but for a greater amount of supplemental irrigation, and for Dry 1 the designs included water harvesting and small-scale storage reservoirs. For Dry 2, large, medium and large scale irrigation systems were part of the adaptation design, with correspondingly different levels of cost per hectare.

⁵ In an economy-wide CGE analysis, after each climate shock the model reallocates inputs to activities and products so as to maximize profits. In certain cases, even after adaptation, marginal returns to inputs may be higher in sectors other than agriculture, so the baseline, no-climate change level of production may not be attained in the scenarios with climate change.

Drainage infrastructure was installed on 1.4 million, 1.0 million, 0.9 million and 0.4 million hectares for the Wet 2, Wet 1, Dry 1, and Dry 2 scenarios respectively. The distribution of the costs between the adaptation components is listed in Table 5.1.

Table 5.1—Summary of adaptation costs in agriculture (annual average 2010–2050, USD million)

Cost elements of the adaptation scenario	Wet 2	Wet 1	Dry 1	Dry 2
Irrigation costs	16.00	30.00	32.00	50.00
Drainage costs	36.78	23.79	21.17	7.50
R&D, farm, and watershed management	16.84	17.14	16.93	10.34
Total	69.63	70.93	70.10	67.84

Source: Authors' calculations.

While the adaptation strategy analyzed here addresses key aspects of sector vulnerability, it is admittedly defined in relatively coarse terms, given the aggregate level of analysis of this research. Future work will be needed to spell out in further detail individual components (and costs) of a more comprehensive adaptation strategy for agriculture, such as for example, specific technologies for livestock, soil or water management; changes in planting dates, crop varieties and cultivars; enhancement of large irrigation schemes, development of small irrigation projects and associate reservoirs in water short areas, on farm water harvesting project, and installing agricultural tile drainage in waterlogged areas.

5.2. Road Transport

The adaptation considered for Ethiopia's road sector consists of a "design strategy" approach that promotes upgraded design standards for roads and bridges to integrate, through the use of enhanced materials and technologies, the risk of increased climate change-related stressors. In this approach, when the road is repaved at the end of its 20-year lifespan, it is repaved according to a design standard that takes into account the increase in climate variability projected over the next 20-year lifespan. This is likely to increase construction costs, but decrease maintenance costs that would have been incurred by using the earlier construction standards.

The costs resulting from adopting the proposed strategy are estimated in Table 5.2. In addition to the enhanced design strategy for paved roads, the costs assume that unpaved roads are re-graded and resealed at five-year intervals, with maintenance costs required within each five-year cycle. These costs are additional to regular maintenance or construction costs.

Table 5.2—Summary of adaptation costs for roads (annual average 2010–2050, USD million)

	Wet 2	Dry 2	Wet 1	Dry 1
Cost increase for new paved roads	2.1	1.9	1.7	1.9
Cost increase for maintaining paved road	4.1	3.5	2.3	5.0
Cost increase for maintaining gravel and earth roads	10.2	7.7	5.5	6.8
Total	16.5	13.1	9.5	13.8
Total (Cumulative total for entire period 2010–2050)	658.4	524.4	379.8	550.4

Source: Authors' calculations.

As illustrated, the costs of adaptation compared to the potential impacts that result from no adaptation make it an imperative to spend a minimal amount up front to avoid significant costs later due to no action. The benefit–cost ratio of this additional expense increases with time, since the strength of climate change signals tend to grow larger in later decades of the century. The longer adaptation is delayed, the greater the expense that must be incurred in doing reactive maintenance.

5.2.1. Adaptation to Flooding

Similar to the process used for examining flooding under a maintenance-only scenario, the adaptation scenario uses a focus of multiplying a cost-per-kilometer factor by the actual pool of roads that may be damaged. The higher cost per kilometer pays for interventions such as drainage, road characteristics, and pavements to enhance flooding resilience (COWI Consulting 2010).

Various incremental cost factors were estimated to reflect the additional cost of the adaptation process. For paved roads, an 11 percent increased factor cost is applied to the base construction cost of all road types⁶.

This cost increase is applied to all roads that are being repaved at the end of their design life cycle, when it is anticipated that a flood of particular severity will occur during the road's projected life span. For this study, the severity threshold considered corresponds to a 20-year flood return period, since this is the standard level of design for paved roads. For roads exposed to a 1 in 20 year flood event, enhanced design standards are applied, which are expected to make them resilient to more severe flood events. Such events would have a 50-year return period under baseline climate conditions, but shorter return periods under climate change.

The analysis of unpaved roads follows broadly the same approach. However, since unpaved roads are on a 5-year rather than a 20-year design cycle, adaptation actions are undertaken on a more frequent basis. For unpaved roads, the cost increase factor is 35 percent, which was derived using the same detailed adaptation analysis process as discussed previously for paved roads. The cost increase factor is higher than in the case of paved roads due to the actions that are necessary to make unpaved roads resilient to flooding. Similar to paved roads, the cost increase factor is applied whenever the return period of floods expected under climate change is shorter than the return period built into baseline design standards.

Table 5.3 summarizes the results of the adaptation cost analysis for roads. The largest costs are associated with adaptation to flooding. Combined, the average annual adaptation costs for both maintenance and flooding are USD 80–90 million per year, except for the Wet 1 scenario where the total rises to USD 117 million per year. Although these costs appear large, they are well justified when compared to the benefits, as discussed in section 5.2.1 below.

Table 5.3—Summary of adaptation costs in the road sector (annual average over the 2010–2040 period, USD million)

	Wet 2	Dry 2	Wet 1	Dry 1
Road maintenance	16.50	13.10	9.50	13.80
Adaptation to floods	71.92	73.17	107.85	67.76
Total cost	88.42	86.27	117.35	81.56

Source: Authors' calculations.

5.2.2. Adaptation in a Benefit–Cost Framework

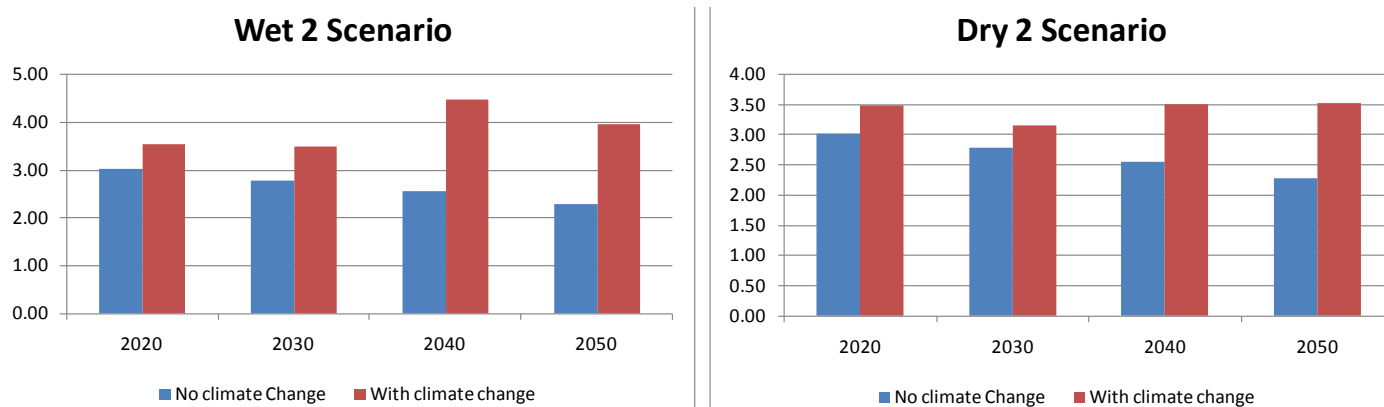
The interventions included in the adaptation analysis, consisting of enhanced design standards so that roads require less maintenance under ordinary weather conditions and are less vulnerable to floods, are likely to make sense (in a benefit–cost sense) even under current climate conditions. However, financial constraints, which limit access to the required incremental capital at construction stage, make their adoption difficult.

But the case for better standards is further strengthened when one accounts for the climate shocks of the future, which are likely to increase the benefits for the same costs of construction and maintenance, in terms of extended life span for the road network and of avoided higher maintenance costs in the future.

A benefit–cost analysis confirms these insights. The benefit–cost ratio of adopting higher design standards is 17 percent to 75 percent higher than in the baseline under the Wet 2 scenario; and 16 percent to 55 percent in the Dry 2 scenario (Figure 5.1). The additional benefit of higher standards become more pronounced in later decades of the time horizon considered, on account of the expected higher frequency or severity of flood events.

⁶ The 11 percent increase factor is obtained by adding up cost increases linked to drainage, road base, and road surface treatments. See also COWI Consulting (2010) for additional information.

Figure 5.1—Benefit–cost ratio of upgrading road standards



Source: Author's compilation.

5.3. Hydropower

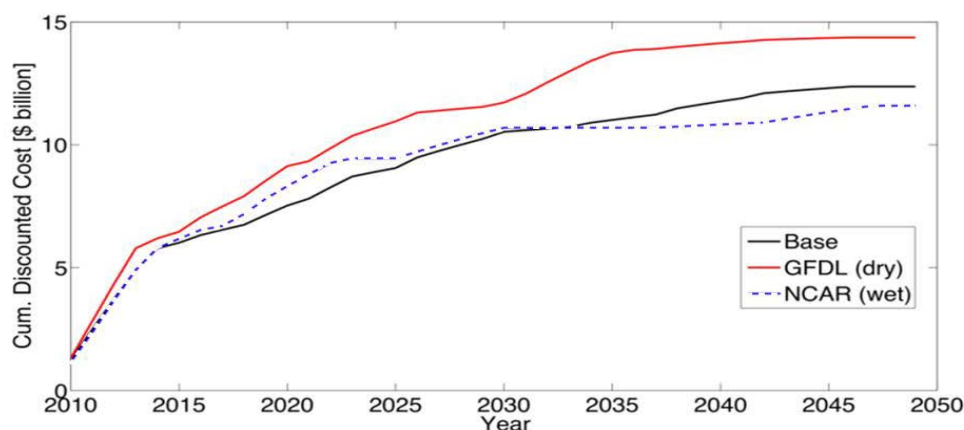
Potential adaptation policy adjustments in the hydroelectric sector include altering the scale and timing of planned projects as well as constraining downstream flow and irrigation flow. Ethiopia has embarked on a very extensive hydropower development program, including major dams on the Blue Nile, Atbara, and Gibe Rivers. Some of these dams are planned as cascades of dams in series and some as dams on parallel rivers. Under “wet” scenarios, climate change may result in higher average river flow so the proposed projects could produce more energy than the base case. Additional economic benefits can be realized or capital cost can therefore be saved by building fewer projects.

On the other hand, drier climate change scenarios would result in lower average river flows and thus reduced energy generation, compared to baseline conditions. Additional dams and power stations can be used to develop greater energy generation potential for the same river flow, as well as developing new dam sites on parallel rivers. The cost of additional capital to keep up with the Ethiopian base-energy generation plan is assumed to be the cost of adaptation in the energy sector ⁷.

The goal of the adaptation analysis was to return the annual energy generation to base (no-climate change) values. With reduced flows and reservoir levels resulting from a drying climate change scenario, energy generation would be reduced. Since in the base development plan only a portion of all of Ethiopia’s potential hydropower is developed, the adaptation strategy is to construct a series of additional hydropower projects to generate the “energy lost” to climate change. The costs for these new plants would be the adaptation costs.

Figure 5.2 shows the additional cost for dry scenario and reduced costs for the wet scenario from the base hydropower investment development plan. The additional costs are incurred by bringing on additional power plants sooner than in the base case. The figure shows cumulative discounted costs. The annual undiscounted cost average over the 2010 to 2050 periods is estimated at USD 100 million.

Figure 5.2—Cumulative discounted cost of hydropower for Ethiopia, Wet and Dry climate change scenarios



Source: Authors' compilation.

Note: Adaptation costs are the difference between Base and Climate Change run. Wet scenario suggests adaptation costs are negative.

⁷ In some cases fossil fuel power stations could be built at an investment lower cost; however, considering the higher fuel cost and Ethiopia’s policy priority to develop its hydropower sector, this option was not considered and removed as an adaptation option.

5.4. Summary of Sector Level Adaptation Costs

By summarizing the results of the sector-wise analyses reported above, it is possible to evaluate the range of total costs (Table 5.4) that Ethiopia would need to incur in order to offset climate change impacts on the sectors analyzed—that is, the cost of actions that would need to be undertaken to achieve the sectors’ development goals, even in the harsher climate of the future.

Adaptation costs vary widely, depending on the climate scenarios considered—on an annual average basis, the range is between USD 158 million to over USD 258 million per year. The highest cost is associated with the Dry 2 scenario, which tends to generate damages (and therefore costs to remediate them) in a consistent manner throughout the period considered; whereas under the Wet 2 scenario, damages (and adaptation costs) tend to cluster in the final decade.

Table 5.4—Summary of sector adaptation costs (annual average 2010–2050, USD million)

	Wet 2	Dry 2	Wet 1	Dry 1
Agriculture	69.6	70.9	70.1	67.8
Road transport	88.4	86.3	117.4	81.6
Hydropower		100.4		25.0
Total annual average	158.0	257.6	187.4	174.4
Cumulative total for entire period (2010–2050)	6,321.9	10,304.0	7,497.9	6,976.2

Source: Authors’ calculations.

5.5. Adaptation: Economy-Wide Analysis

The sector-based analysis of adaptation reported above is just one part of the whole picture. To get a better representation of efforts needed to adapt, it is necessary to consider the opportunity cost of diverting scarce investment resources from ordinary development objectives to enhancing the economy’s resilience to climate change. For example, building stronger roads might entail less resources to build hospital or schools.

To include these indirect effects into the analysis, sector level adaptation costs are incorporated into the CGE model described in section 3.3. In particular, the economy-wide effects of undertaking the following adaptation strategies are analyzed.

An expanded investment program in **roads** is analyzed. Such program includes increasing the share of paved and hardened roads, as well as “soft” measures, such as changes in transportation operation and maintenance, development of new design standards that consider projected climate changes, transfer of relevant transportation technology to stakeholders, and the enhancement of transportation safety measures. The associated adaptation costs were included in the model. They increase the road infrastructure investment plan for Ethiopia.

In the case of **dams**, adaptation consists of altering the scale and timing of planned dam construction and hydropower projects, as well as constraining downstream flow and irrigation flow. In the CGE model, the costs of the dams and hydropower investments are assumed to be financed by foreign borrowing. The annual costs (with higher requirements under the “dry” scenarios) are calculated as the interest charges (at 5 percent) on the cumulated debt in each period.

The model incorporates **irrigation** and water management investments. In the adaptation scenarios, the assumption is that the share of irrigated land and land benefiting from better water management increases over time more than in the base scenario. The incremental costs of these investments have been estimated and incorporated in the model. There is also a tradeoff between water used for irrigation and for power generation. In the Dry 2 scenario with adaptation, we assume that policy favors irrigation, with some loss of hydropower production and exports as a result.

5.5.1. Adaptation Costs

In addition to the direct costs of adaptation investment project (additional to the investment program in the base run—see Table 5.4), a general equilibrium analysis was undertaken to estimate direct and indirect costs of adaptation. In the general equilibrium approach, the total cost of adaptation investments includes the opportunity cost of the resources diverted from gross fixed capital formation (GFCF). The general equilibrium analysis includes the measure of benefits that are foregone as a result of diverting resources towards adaptation investment, resources that would be otherwise employed to support Ethiopian development programs.

When indirect costs are included in the analysis, adaptation turns out to be significantly more expensive (Table 5.5) than the sector-wise analysis would suggest. The sum of sector-related and indirect, economy-wide costs is in the range of

USD 0.8 to USD 2.8 billion per annum: direct sector costs account for some 7 to 24 percent, a relatively small share of the total.

Table 5.5—Adaptation costs: direct and indirect components (annual average 2010–2050, USD million)

Scenario	Direct, sector level costs	Indirect costs	Total direct and indirect costs
Wet 1	0.19	0.60	0.79
Dry 1	0.17	0.77	0.94
Wet 2	0.16	2.30	2.46
Dry 2	0.26	2.55	2.81

Source: Authors' calculations.

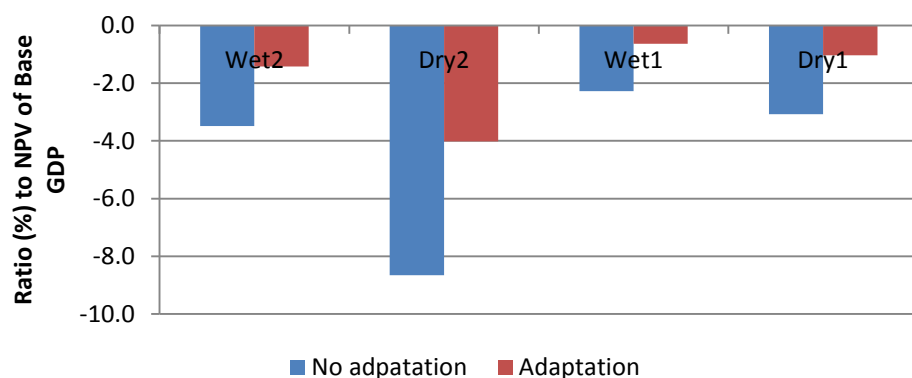
The results show that adaptation costs in the various scenarios differ a lot. Adaptation in the dry scenarios involves expensive increased investment in dams, irrigation, and hydropower, while adaptation in the wet scenarios involves relatively major investments in improved roads, which is especially evident in the later periods.

There are differences in foreign saving in the adaptation cost scenarios. The Dry 2 scenario involves the largest increase in dams and hydropower investment, which results in the largest change in foreign savings as Ethiopia services the increased foreign debt to finance the investment. In the Dry 2 scenario, the additional investment costs impose interest charges that significantly reduce foreign saving (the current account balance). By contrast, in the Wet 2 scenario, the lower construction costs and hence lower foreign debt lead to increases in foreign savings relative to the base run. The dry scenarios are more damaging to investment overall, while the wet scenarios are most damaging in the latter years, with magnitudes close to those of the dry scenarios. Not surprisingly, costless adaptation⁸ is the most beneficial. Costly adaptation always yields higher GFCF in all years compared to the no-adjustment scenario, indicating the success of costly adaptation to generate increased savings and investment.

5.5.2. Welfare Analysis

Figure 5.3 presents the effects of adaptation on economic well-being (measured here as NPV) for the different climate scenarios. The results indicate that adaptation investments significantly offset (but do not eliminate) the impact of climate change shocks and improve welfare in all scenarios, even in the case of adaptation investments with potential “regrets”, such as the building of costly dams which may not be needed in the Wet scenarios.

Figure 5.3—Net Present Value (NPV) of absorption differences



Source: Authors' compilation.

Note: NPV of Absorption, Difference from Base (% of NPV of GDP). Absorption is defined as GDP, plus imports minus exports.

The Dry 2 scenario has a much bigger impact in all periods, while the Wet 2 scenario has a dramatic impact in the last decade (with three 100-year floods in that period). Adaptation also significantly reduces variability of agriculture GDP growth compared to the no adaptation scenario.

⁸ Adaptation not involving any expenses.

5.5.3. Benefit–Costs Assessment

The adaptation strategy analyzed here appears to be quite sensible in a benefit–cost perspective. Table 5.6 provides data on the net gains from adaptation and the direct costs of the various adaptation projects assumed to be undertaken in the adaptation scenarios. The net gains are measured using the CGE model and are measured by the difference in total welfare (absorption) between the climate change shock scenario and the same scenario with costly adaptation.

Table 5.6—Net benefits and adaptation project costs, USD billions

Scenarios	Welfare losses		Net gain	Project costs	Benefit–cost ratio
	With adaptation	Without adaptation			
Wet 2	-61.48	-131.80	70.32	6.32	11.1
Wet 1	-17.67	-55.60	37.93	7.50	5.1
Dry 1	-32.67	-88.41	55.74	6.98	8.0
Dry 2	-124.06	-264.59	140.54	10.30	13.6

Source: Authors' calculations.

Notes: Cumulated losses and costs over the period 2010–2050, no discounting.

The results are dramatic. The mix of infrastructure projects in the adaptation investment programs (hydropower, irrigation, water management, and roads) yield very high benefit–cost ratios. Adaptation reduces the losses from the climate change shocks by over half, and the investment costs are much lower than this gain in all cases. In the worst scenario, Dry 2, the benefit–cost ratio is highest, which indicates that these projects are very worthwhile. Discounting does not change these results.

5.5.4. Closing the Welfare Gap Caused by Climate Change

Sector-wise adaptation enables the achievement of sector level objectives in a cost-effective manner. But it also entails the opportunity cost of diverting resources toward investment in climate resilience, and therefore it does not necessarily enable Ethiopia to fully eliminate the welfare impacts of climate change. What would it take to “make the economy whole” again? Two options are explored in this section.

The first is to estimate the “residual compensation costs” as the transfers (in USD) that would be required to completely offset the loss of absorption from climate change shocks, after implementing adaptation investments. The results are reported in Table 5.7. The Dry 2 scenario has the largest residual compensation costs, while the impact of the increased number of extreme floods in the last decade generates large losses in the Wet 2 scenario, which are only partly reduced by adaptation investment projects. Closing the “welfare gap” through residual compensation would entail mobilizing a volume of resources much larger (Wet 2 and Dry 2 scenarios) than in the case where only adaptation costs are addressed.

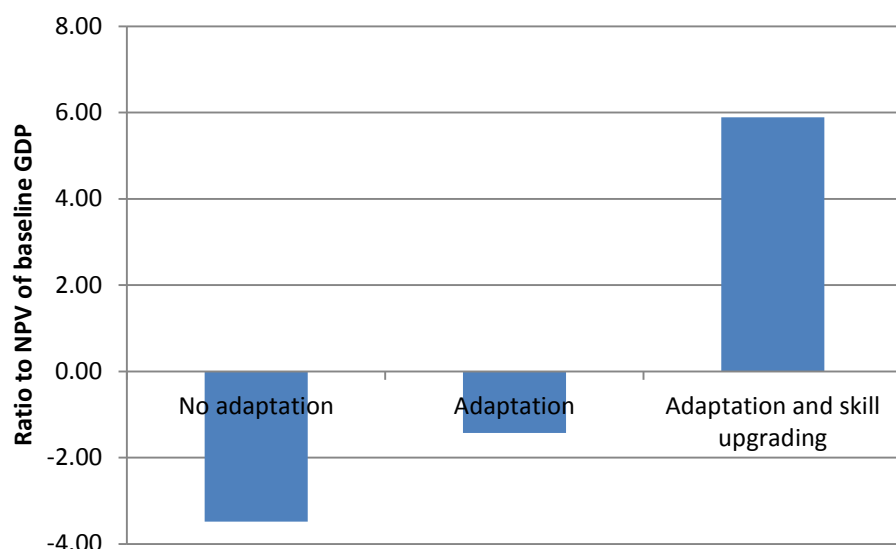
Table 5.7—Adaptation costs, and residual damage (annual average 2010–2050, USD billions)

Scenarios	Adaptation costs	Residual damage	Total
Wet 2	2.45	1.52	3.97
Wet 1	0.79	0.43	1.22
Dry 1	0.94	0.81	1.75
Dry 2	2.81	3.03	5.84

Source: Authors' calculations.

The second approach is to include an additional labor-upgrading program in the adaptation strategy. In this scenario, 0.1 percent of rural unskilled labor is assumed to be transferred to the urban region, with additional upgrading so that all the urban labor categories, skilled and unskilled, grow uniformly faster than in the base run. When tested under the Wet 2 scenario, an adaptation strategy including such a labor upgrading program appears to be able to more than offset the negative impacts of climate change (Figure 5.4).

Figure 5.4—Discounted differences in absorption from baseline (2010–2050, Wet 2 scenario)



Source: Authors' compilation.

Note: NPV of Absorption, Difference from Base (% of NPV of GDP). Absorption is defined as GDP, plus imports minus exports.

While no information was available within the analysis' time frame to properly cost the skill-upgrading program, this finding points to the significant potential benefits of accelerating the diversification of the economy away from highly climate sensitive sectors, such as agriculture. In the Wet 2 scenario, for any value of the program cost below USD 1.5 billion per year, a development strategy including a skill-upgrading program like the one considered here would appear to be preferable to the residual compensation approach.

6. IMPLICATIONS FOR POLICY AND RESEARCH

Historically the Ethiopian economy has been vulnerable to climate fluctuations. The analysis of this paper shows that climate variability will increase under all scenarios. Robust growth is likely to be the first and best line of defense against climate change impacts. A long-term investment program to promote growth and adaptation to climate change should take into account Ethiopia's current dependence on agriculture and the importance of infrastructure investment. Such an approach could be articulated for both the shorter term, including the implementation of the Growth and Transformation Plan (GTP), issued by the government, and for the longer term.

Short–Medium Term

Investments in improved agricultural productivity and access to markets such as watershed management, on-farm technology, access to extension service, transport, fertilizers and improved seed varieties, and climate and weather forecasting will enhance the resilience of agriculture, both to droughts and to waterlogging caused by floods.

Modeling results show that existing road design standards (level of prevention against extreme events, e.g. local and regional flooding) are inadequate to address current climate variability and will impact economic growth rates in the near- and mid-term. Results from climate change analyses show that this issue is likely to become worse in the mid- to long-term.

Even under current climate conditions, the direct benefits—in terms of increased lifetime—of roads designed following higher standards outweigh the corresponding costs in the discounted benefit–cost analysis reported in section 5.5.3. The case for improved design standards is even stronger under climate change, irrespective of climate outcomes: the benefit–cost ratio of adopting higher design standards is 17 percent to 75 percent higher under the Wet 2 scenario than in the baseline; and 16 percent to 55 percent under the Dry 2 scenario. In addition, there are important indirect economy-wide benefits: a more climate-resilient road network can avoid costly disruptions of communications links and supply chains that increased flood frequency might bring about. An important issue to consider is whether building fewer, but more climate resilient roads, is preferable to building a larger number of roads to lower design standards that are likely to be more vulnerable to climate shocks.

While in the longer term hydropower development will become increasingly more climate-sensitive, projects in the current pipeline are likely to be less vulnerable to shocks as the overlap between their lifespan, and the time when stronger climate change effects will materialize, is relatively limited. Some climate change scenarios actually project an increase in Ethiopian runoff, resulting in larger volumes of hydropower generation, and thus making the case for investment in hydropower stronger.

Strengthening of the electricity sector—in particular the promotion of regional and Africa-wide power grids to provide markets for Ethiopia’s excess power—should be a priority in the investment strategy. Strengthened hydropower development can both increase near-term economic growth and make the energy system more climate-resilient: more reservoir storage distributed over the country provides more reliability and protection from regional droughts.

Longer Term

Since agriculture (the economy’s most climate sensitive sector) is likely to remain for some time a major engine of growth, climate-induced shocks will continue to be a threat to macro-economic stability, because of the impacts on income, employment, fiscal revenues, capital formation, drain on government expenditure and aid flows to support disaster relief, etc.

Under climate change, renewed efforts will be necessary to buffer the economy from more frequent or severe climate shocks. These include strengthening social safety nets, access to relief funds, drought early warning systems, crop insurance programs, grain banks, and strengthening infrastructure design.

In the longer term, however, accelerated diversification of income and employment sources away from climate-sensitive sectors such as agriculture is likely to become increasingly important under a more erratic climate, particularly because diversification holds promise to be a cost-effective way to eliminate residual welfare damage caused by climate change. Particularly important will be the absorption of rural labor into non-agriculture activities, including through skills-upgrading programs and encouragement of growth poles around medium size municipalities.

As we move towards mid-century, the range of possible climate futures broadens to encompass markedly different “wet” and “dry” scenarios. This has implications for the optimal timing of dams and other investments in water infrastructure, which is likely to be quite sensitive to climate outcomes. Large projects of this type should be subject to careful climate-robustness tests. Better data on hydro-meteorological processes, and stronger capacity to analyze and model them, is key to make more informed decisions on issues such as the number of hydropower plants, the design of individual plants, and the operation of the grid.

Under “dry” future climate scenarios, competition among users of water (e.g. municipal and industrial consumption, hydropower generation, and irrigation) might become more acute, particularly in certain river basins. The availability of water to downstream riparian countries might also be affected.

Given the significant pay-off of addressing internal and transboundary conflicts on water use before they arise, the government might want to consider investments into river basin planning systems and institutional arrangements that can facilitate information sharing, dialogue, and dispute resolution.

Implications for Research

Apart from the implications for national policy makers, the results from the Ethiopia case study help draw some lessons for the broader research agenda on adaptation to climate change. In terms of the insights the analysis has generated, it is worth noting the following:

- Sector-based analysis tends to underestimate significantly the range of impacts and adaptation costs: in the present analysis, the sector-related component of adaptation account for some 7 percent to 24 percent of the total costs. Inclusion of indirect effects through economy-wide analysis seems essential for informing policy makers;
- Among the vehicles transmitting climate shocks across the economy, damages to physical infrastructure (particularly roads and bridges) due to extreme events, have a very important role;
- Adjustments to existing development plans can reduce climate change damages, but they are unlikely to eliminate them altogether. Accelerating the structural transformation of the economy may deserve closer scrutiny as a strategy to reduce climate vulnerability.

In terms of the implications for future research, the analysis presented in this paper points to the following areas:

- The stochastic nature of climate change shocks and the inherent uncertainty in climate models requires further work on the analysis of adaptation options that can minimize the chances of “regrets”. Rather than “optimal” deci-

sions, policy makers will increasingly need tools for making “robust” decisions. That is, decisions that “make sense” under a wide range of climate outcomes;

- Climate change is likely to affect a wide range of sectors, which makes it necessary to deploy multiple tools for adequate impact analysis. While in some cases a number of relatively well established tools are available (e.g. crop modeling, hydrological and flood analysis, etc.), more work appears necessary to address adequately other types of effects, such as impacts on human health, provision of ecosystem services, etc.;
- This paper has conducted an analysis at a level of spatial disaggregation suitable to inform national or sector level policy discussions. A finer degree of resolution (both in time and space) will be necessary to inform decision making at the level of specific programs or projects. However, there is a trade-off between the level of detail of the analysis and the margin of error of the results. More work is needed to find ways to relax that trade-off and enable researchers to deliver higher resolution projections without expanding the range of uncertainty of the findings.

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