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The Economic Impacts of Climate Change in Ethiopia: A CGE Analysis

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Abstract

A multi-country, multi-sector computable general equilibrium (CGE) model is used for the first time to evaluate the impacts of climate change on Ethiopian agriculture and the overall economy. This analysis uses the GTAP[1] 9 Database and the GTAP-W model that distinguishes between rainfed and irrigated agriculture, and implements water as a directly substitutable factor of production in the production process of irrigated agriculture. Two global emissions scenarios (A1 and B1) from two global circulation models (GCM) (CSIRO[2] and MIROC[3]) in 2050 are used to evaluate the economy-wide impacts of climate change on Ethiopian agriculture. The study reveals that climate change depresses agricultural production resulting in a significant rise in crop market prices. Further, climate change depresses economic growth and welfare, and tends to deepen poverty and food insecurity in the country.

1 GTAP: Global Trade Analysis Project.
2 CSIRO: Commonwealth Scientific and Industrial Research Organization; abbreviation for the CSIRO-Mk3.0 general circulation model (Nelson et al. 2010)
3 MIROC: MIROC 3.2 medium resolution general circulation model, produced by the Center for Climate System Research, University of Tokyo, the National Institute for Environmental Studies, and the Frontier Research Center for Global Change, Japan (Nelson et al. 2010).

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1. Introduction

The Ethiopian economy is anchored in the agricultural sector. Agriculture accounts for 32.6 percent of the national gross domestic product (GDP), contributes 77 percent to export trade and is a livelihood source for 72.5 percent of the country's labor force (FDRE 2020). However, the country's agriculture is predominantly a rainfed subsistence activity, characterized by low productivity and high vulnerability to rainfall variability. Hydrological variability costs the country more than one-third of its economic growth potential (World Bank 2006), contributing to severe poverty (Bundervoet et al. 2020) as well as food and nutrition insecurity which pose serious challenges to the country (Berhane et al. 2018a; Berhane et al. 2018b; MoA 2019a; MoA 2019b). Poverty is widespread, especially among rural households that principally rely on agriculture for their livelihoods. The development of the agricultural sector is therefore crucial for economic growth and poverty alleviation in the country. Agricultural development has played a significant role in enhancing growth and reducing poverty in several regions around the world (e.g., Valdes and Foster 2010; Christiaensen et al. 2011), and could play a similar role in a developing country like Ethiopia.

Agriculture in Ethiopia is a climate sensitive sector and is highly vulnerable to the vagaries of nature. Uncertainties related to climate change pose serious challenges to the agricultural sector and could have profound repercussions on agricultural production and the country's overall economic conditions. The potential for agricultural production will be significantly affected by climate change induced variations in temperature and rainfall patterns, in addition to the related impacts from altered water availability and extreme weather events. Climate change is expected to affect water resources (Bates et al. 2008) and may therefore impose severe constraints on their use in agricultural production. Climate change will also inevitably result in higher evaporation rates and water demands (Conway 2005) as well as increase crop water requirements and reduces agricultural yields (Blackmore and Whittington 2008). Projections indicate that the variations in rainfall, temperature, and seasonality will dramatically impact Ethiopia (Evangelista et al. 2013) and the country remains highly vulnerable to climate change (Conway and Schipper 2011). Given the significance of agriculture in Ethiopia, climate change induced shocks affecting the agricultural sector will have serious repercussions on the entire economy deepening the already precarious conditions of poverty and food security in the country. Analysis of the impacts of climate change on Ethiopia's economy is therefore an important component of the country's policy and research agenda.

Different modeling approaches have been applied to assess the economic impacts of climate change. These include partial equilibrium models like crop simulation models, agro-ecological zone (AEZ) models, and Ricardian models that analyze only a specific part of the economy, typically agriculture (e.g. Reilly et al. 1996; Deressa 2007; and Deressa and Hassan 2009; Malua 2009; Gbetibouo and Hassan 2005; Kabubo-Mariara and Karanja 2007). Results from some of these modelling exercises indicate that climate change will lead to reduced net crop farm revenue in Ethiopia (Deressa and Hassan 2009) in, Cameroon (Malua 2009), and Zimbabwe (Mano and Nhemachena 2006). Similar studies also confirm the adverse effects of climate change on crop production in Kenya (Kabubo-Mariara and Karanja 2007), and South Africa (Gbetibouo and Hassan 2005). However, these studies only examine the effects of climate change on a specific sub-sector of the entire economy (crop production) in a partial equilibrium setting. The partial equilibrium nature of the modeling approach employed in these studies means that they are unable to account for inter-sectoral linkages and important economic feedback mechanisms. They are also constrained in their analysis of the relationships between prices and quantities which is required to comprehensively evaluate climate change impacts.

Computable general equilibrium (CGE) models, on the other hand, capture various inter-sectoral linkages and relevant economic feedback processes to evaluate the economy-wide effects of climate change. Due to their general equilibrium feature, CGE models determine relative product and factor prices endogenously via market-based interactions among economic agents so that product and factor markets attain their equilibrium through the adjustment of prices. CGE models are thus capable of demonstrating how climate change impacts are propagated across sectors and countries (Ginsburgh and Keyzer 1997) and are suitable for analyzing the direct as well as indirect impacts of climate change in a comprehensive manner. Climate change induces direct and indirect effects across sectors which calls for analysis of inter-sectoral linkages. CGE models are therefore an appropriate modeling approach to assess the aggregate economic impacts of climate change in Ethiopia. This study uses a global computable general equilibrium (CGE) modeling framework, based on the revised version of the GTAP-W model (Calzadilla et al. 2010), to analyze the impacts of climate change on Ethiopia's agricultural sector and the overall economy in 2050.

CGE models have been used to investigate different issues including the assessment of climate change impacts on water availability and agricultural production worldwide (Calzadilla et al. 2013a). They have also been used in the analysis of potential impacts of climate change and trade liberalization on global agriculture (Calzadilla et al. 2011). The findings show that climate change will reduce global food production, welfare and GDP as well as raise food prices over time (Calzadilla et al. 2011; Calzadilla et al. 2013a). Similar results were found by Kahsay et al. (2017a), who evaluated the economic impacts of climate change and irrigation development in the Nile basin. In evaluating the economic and water resource availability effects of climate change and trade liberalization in the Nile basin, Kahsay et al. (2017b), also find that in the short term (up to 2025), climate change will improve water supply and irrigation water use, enhancing economic growth and welfare in the Nile basin. CGE models have also been applied to analyze the economy-wide impacts of adaptation strategies to climate change. CGE analysis on the impacts of expanding irrigation and increasing agricultural productivity as adaptation strategies for climate change in Sub-Saharan Africa (Calzadilla et al. 2013b) reveals that an increase in productivity achieves better outcomes compared to an expansion of irrigated area due to the low baseline level of irrigated area in the region Similar results are found by Calzadilla et al. (2014), who explored two alternative adaptation scenarios (yield improvement and irrigation development) to climate change impacts in South Africa.

A few CGE models have been used to assess the broader impacts of climate change on Ethiopia's economy (Gebreegziabher et al. 2015; Mideksa 2010; Yalew et al. 2018; Robinson et al. 2011; Solomon et al. 2021). The findings reveal that climate change would reduce agricultural production and result in a substantial reduction in GDP (Gebreegziabher et al. 2015; Yalew et al. 2018; Robinson et al. 2011). Modelling results also show that climate change increases income inequality (Mideksa 2010) and affects the poor disproportionately (Robinson et al. 2011; Solomon et al. 2021). Compared to those previous studies, this study represents the first effort to apply a global CGE model to analyze economy-wide impacts of climate change on Ethiopia's agricultural sector and the economy. In analyzing the impacts of climate change on Ethiopian agriculture and the economy, this study also constitutes the first effort to distinguish between rainfed and irrigated agriculture and to incorporate water as a separate factor that is directly substitutable with other factors in the production process of irrigated agriculture. It also uses a reliable global database referred to as the Global Trade Analysis Project database (the GTAP database) and a highly disaggregated agricultural sector. Unlike previous studies on the impacts of climate change on Ethiopian agriculture, this study considers the impacts of climate change-induced carbon fertilization on crop yields. Moreover, the study considers numerous economic indicators in evaluating the impacts of climate change on the Ethiopian economy.

2. Economic models of climate change

The economic impacts of climate change have been assessed in existing literature using partial and general equilibrium modeling approaches. Partial equilibrium analysis is specifically used to evaluate climate change impacts on agriculture and is categorized into three approaches: crop simulation models, agro-ecological zone (AEZ) models, and Ricardian models (Mendelsohn and Dinar 1999; Zhai et al. 2009). Crop simulation models estimate crop yield responses to climatic variations under controlled experiments using the results of general circulation models (GCM) (Mendelsohn and Dinar 1999). Some studies that use crop simulation models have examined the adverse effects of warming on crop yields in developing countries (Rosenzweig and Parry 1994; Reilly et al. 1996). The major limitation of these models is that they neglect farmers' adaptation strategies for coping with climate change and so they tend to overestimate the impacts of climate change on agricultural production (Mendelsohn and Dinar 1999; Zhai et al. 2009).

The second approach is the AEZ model (also known as crop suitability approach) which analyzes land suitability for crop production based on crop characteristics, existing technology, as well as soil and climatic factors (FAO 1996). AEZ analysis combines crop simulation models with land management decision analysis. It categorizes existing land by agro-ecological zones, which differ in the length of growing period and climate (Darwin et al. 1995; Fischer et al. 2005). These models share the limitations of the crop simulation models in that they neglect the effect of farmers' adaptation strategies to changing climatic conditions (Mendelsohn and Dinar 1999; Zhai et al. 2009). Further, AEZ models rely on simulated crop yields which are often higher than actual yields (Zhai et al. 2009).

Mendelsohn et al. (1994) proposed the Ricardian model in order to address the limitations of the crop simulation and AEZ models. The Ricardian cross-sectional approach analyzes the relationship between land value and climate variables (usually temperature and precipitation) in addition to a host of other variables based on statistical estimates from survey data. The Ricardian approach has been widely applied to assess climate change impacts on agriculture in different parts of the world. Deressa (2007) and Deressa and Hassan (2009), for example, used the Ricardian approach to analyze the impacts of climate change on Ethiopian agriculture and described farmers' adaptations to varying environmental factors. This approach has also been used to assess the economic impacts of climate change on agriculture in Cameroon (Malua and Lambi, 2007), Zimbabwe (Mano and Nhemachena 2006), Kenya (Kabubo-Mariara and Karanja 2007), South Africa (Gbetibouo and Hassan 2005), and the United States (Mendelsohn et al. 1994). Unlike the crop simulation and AEZ models, the Ricardian approach incorporates climate change adaptations by farmers. However, the approach is limited as it fails to account for price changes and does not fully control for the impact of other variables that affect farm incomes (Mendelsohn and Dinar 1999; Cline 1996).

Besides their respective weaknesses, the partial equilibrium models outlined above collectively share a major limitation that curtails their analytical capacity to provide a comprehensive analysis of the economic impacts of climate change. Due to their partial equilibrium nature, these models only depict part of the overall economy, focusing solely on the agricultural sector. The models assume that there are no inter-sectoral linkages and relevant economic feedbacks across sectors. Moreover, as partial equilibrium models, they are considered incomplete as they fail to capture the potentially important relationships between commodity prices and quantities. Prices are treated as exogenous factors, but in reality, output changes are expected to affect product prices. Changes in input demand may also be reflected in input prices.

Climate change is expected to have direct and indirect effects on various sectors of the economy. Inter-sectoral linkages therefore have to be considered when assessing the impacts of climate change on agriculture. A computable general equilibrium (CGE) model is an appropriate modeling approach to capture the interactions between agriculture and other sectors. Unlike partial equilibrium models, CGE modelling accounts for various inter-linkages between economic sectors to analyze economy-wide effects that could occur as a result of climate change. Moreover, CGE models determine relative product and factor prices endogenously so that product and factor markets attain equilibrium through the adjustment of prices.

A few studies have used CGE models to examine the impacts of climate change on the Ethiopian economy. Gebreegziabher et al. (2015) used a countrywide CGE model to analyze the impacts of climate change on Ethiopian agricultural performance. Their results project that agricultural productivity reductions are associated with a 20 percent decline in average income over a 50-year period. Yalew et al. (2018) assess the economy-wide and regional effects of climate change-induced productivity and labor supply shocks on Ethiopian agriculture. Their results show a worst-case scenario of an 8 percent decline in national GDP. Using dynamic CGE modelling, Robinson et al. (2011) examined the impacts of climate change in Ethiopia. Their results showed that climate change induces a 10 percent decline in GDP by 2050, with disproportionate impacts on the poor. Mideksa (2010), estimated the economy-wide impacts of climate change in Ethiopia including its distributional consequences using a general equilibrium model. The study showed that climate change hampers economic growth in two ways. First, climate change-induced declines in agriculture and connected sectors would reduce the country's

GDP by about 10 percent. Second, climate change would raise the degree of income inequality by increasing the Gini coefficient by 20 percent, which would likely further decrease economic growth and deepen poverty. A recent study by Solomon et al. (2021) presented the economy-wide impacts of climate change on agricultural production in Ethiopia using dynamic computable general equilibrium modelling. The authors simulated climate change-induced shifts in agricultural productivity up to the year 2050. Their results showed considerable declines in crop production resulting in a substantial reduction in agricultural GDP. Moreover, climate change was found to have more effects on the incomes and consumption of poor rural households than on urban and rural non-farming households.

3. Modeling framework and data

3.1. Modeling framework

The modeling framework applied in this study is the Global Trade Analysis Project (GTAP) model (Hertel 1997) developed at the Center for Global Trade Analysis, Purdue University, USA, for use in global trade analysis. GTAP provides a global modeling framework (the standard GTAP model) and a common global database (the GTAP database) that offer researchers the opportunity to conduct modelling and policy simulations.

GTAP is a static comparative, multi-regional, multi-sectoral CGE model of the world economy that examines all aspects of an economy with its general equilibrium feature. The GTAP model consists of accounting relationships, behavioral equations and the global sectors required to complete the model. The model's accounting relationships ensure the balance of receipts and expenditures for every agent identified in the economy, while the behavioral equations specify the behavior of profit and utility optimizing agents in the economy through production and demand functions based on microeconomic theory (Brockmeier 2001). The GTAP model assumes perfectly competitive markets, constant returns to scale technology, a non-homothetic demand system and a foreign trade structure characterized by the Armington (1969) assumption. Assuming weak separability, the production system is set up as a series of nested constant elasticities of substitution (CES) functions combined through elasticities of substitution.

Each region or composite region in the GTAP model has a single representative regional household with fixed endowments (primary factors of production). This regional household derives income from the sale of primary factors to the producers (firms), which combine them with composites of domestically produced and imported intermediate goods (inputs) to produce final goods. These final goods are in turn sold domestically to private households and the government, and also exported to other regions including the rest of the world. Based on an aggregate utility function, the regional household allocates the available regional income across three categories of final demand: private household expenditures, government expenditures and national savings. The aggregate regional utility is specified as a Cobb-Douglas function with fixed expenditure shares on the three components of final demand (Hertel and Tsigas 1997) so that a rise in regional income implies equiproportional changes in the final demand.

The private household buys commodity bundles to maximize utility, subject to expenditures (budget constraints). The constrained optimizing behavior of the private household is represented in the GTAP model by a non-homothetic Constant Difference of Elasticity (CDE) function (Hertel and Tsigas 1997), which implies that the expenditure shares of various commodities change as income levels vary. Following the Armington assumption (Armington 1969), the private consumption bundles are modeled as CES (constant elasticity of substitution) aggregates of domestic goods and imported bundles, where imported goods are themselves CES aggregates of imports from different regions (Arrow et al. 1961). Likewise, government consumption is given by a CES aggregate of domestically produced goods and an Armington aggregate of imports.

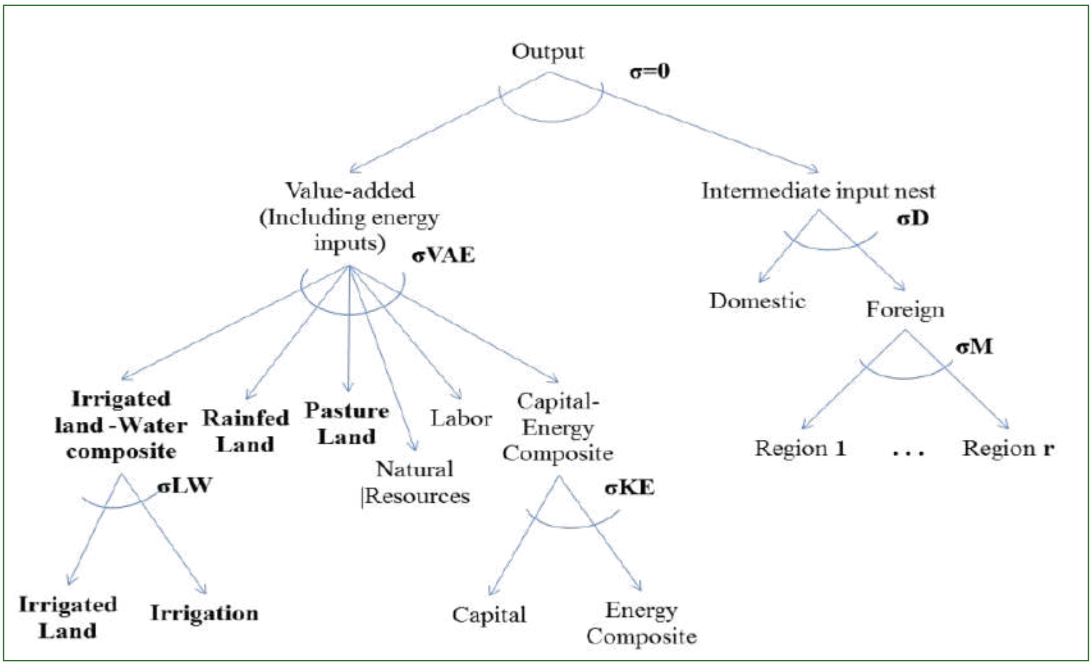
Investment in each region is financed from a global pool of savings. Each region contributes a fixed proportion of its income to the savings pool. In the standard GTAP model, two alternative methods are used to allocate the savings pool in each region. The first is where changes in regional shares are proportional to changes in the aggregate savings pool. The second is where investments are allocated according to the prevalent relative rates of return. Investments in the GTAP model are assumed to be driven by savings (Brockmeier 2001) such that savings are completely used up on investments.

The GTAP model also includes two global sectors: a global banking sector and a global transportation sector. Global banking intermediates between global savings and regional investments by assembling a portfolio of regional investment goods and selling shares in this portfolio to regional households to meet their savings demands. A global transport sector provides international transport services that account for the differences between the *fob* (free-on-board) value of exports and *cif* (cost, insurance and freight) values of imports for traded commodities. The sector assembles regional exports of trade, transport and insurance services and also produces a composite good used to move merchandise trade among regions (Hertel and Tsigas 1997).

The behavioral equations of the GTAP model specify the behavior of optimizing agents based on neoclassical economic theory. Producers are modeled through a representative firm, which maximizes profits using primary factors of production. The GTAP model assumes perfectly competitive markets and involves constant returns to scale (CRS) technology. Profit maximization in a perfectly competitive market implies zero pure economic profit conditions, which in turn implies that firms' revenues are completely exhausted on expenditures for intermediate and primary factors of production. Given the assumption of CRS technology (i.e., linearly homogenous production function) and the fact that the price equations in the model constitute the first order derivatives of the production functions, the GTAP model is essentially homogenous of degree zero in prices. Demand for primary factors among firms therefore only depends on the relative factor prices.

The analysis in this study will use the new version of the GTAP-W model (Calzadilla et al. 2010), which is a refinement of the GTAP-W model introduced by Berrittella et al. (2007). The basic change in the new GTAP-W model is reflected in a new production structure that splits the land endowment in the value-added nest into rainfed land, irrigated land and irrigation water. Unlike the original GTAP-W model that incorporates water into the production structure as a non-substitutable factor of production, the revised GTAP-W model distinguishes between rainfed and irrigated agriculture and implements water as a factor of production directly substitutable in the production process of irrigated agriculture (Figure 1).

Figure 1: Revised GTAP-W Model: Truncated nested production structure



Source: Calzadilla et al. (2010).

3.2.Data

The GTAP model has a common database, referred to as the GTAP database of the world economy. The database contains complete bilateral trade information, transport and protection data. The GTAP 9 database is used in this study. The GTAP 9 database includes 140 regions and 68 commodities and features across three reference years (2004, 2007, and 2011) (Aguiar 2016). More specifically, the GTAP-Power 9 database, an electricity-detailed extension of the GTAP 9 database, which disaggregates the electricity sector in the GTAP 9 database into 12 sub-sectors (Peters 2016) is used in this study. The latest database reference year (2011) is used as a baseline for this study. The 140 regions in the GTAP-Power 9 Database are aggregated into eight regions: Egypt, Ethiopia, Sudan (including South Sudan), the Equatorial Lakes (EQL) region, Rest of East Africa, Rest of North Africa, Rest of Sub-Saharan Africa and Rest of the World (ROW) (See Appendix A). The four EQL countries covered in the GTAP 9 Database are Rwanda, Kenya, Tanzania and Uganda. In the GTAP 9 database, Sudan is represented within a composite region termed the Rest of East Africa. The SplitReg Program (Horridge 2011a) is employed to split off Sudan from the composite region (Rest of East Africa Region) based on Sudan's share of the region's total value of endowments. The split database is verified using the GTAP Adjust Program (Horridge 2011b).

The 68 sectors in the GTAP-Power 9 Database are aggregated for the purpose of this study into 20 sectors, 8 of which are agricultural sectors and 12 non-agricultural sectors (See Appendix B). Following Calzadilla et al. (2011), the agricultural land endowment in the standard GTAP database is disaggregated into rainfed land, irrigable land, and irrigation water based on available IFPRI data (Nelson et al. 2010). The relative share of rainfed and irrigated production in total production is used to split the land rent in the original GTAP database into a value for rainfed land and a value for irrigated land for each crop in each region. In the next step, the ratio of irrigated yield to rainfed yield is used to split the value of irrigated land into the value of irrigable land and the value of irrigation water. Due to the lack of data, the values for the elasticity of substitution between irrigated land and irrigation water used in this study are adapted from Calzadilla et al. (2011).

4. Baseline and climate change scenarios

4.1. Baseline scenario

The model examines the economy-wide impacts of climate change on agricultural production and the overall Ethiopian economy in 2050. Climate change will impact Ethiopia's future economy. These impacts are therefore evaluated relative to a benchmark equilibrium based on the assumption of a future with no climate change. The method proposed by Dixon and Rimmer (2002) is employed to obtain the future benchmark equilibrium dataset for the GTAP-W model.

Projected values that reflect expected changes in global macroeconomic variables are used to obtain baseline conditions in a future with no climate change. More specifically, cumulative growth rates in real GDP, population, capital stock, labor supply, agricultural land (rainfed and irrigated) and irrigation water are used to construct the future baseline. Expected changes in rainfed and irrigated land use and irrigation water allocation across crops and regions are based on data from Nelson et al. (2010) who provide detailed baseline data for the year 2000, and simulation data until the year 2050 with respect to irrigation water use, crop yields and cropped area in 126 river basins. These data distinguish between 20 rainfed and irrigated crops, and 281 food processing units (FPU) for 115 economies, including Ethiopia.

The base year of the GTAP-Power 9 database used in this study is 2011, so the baseline equilibrium is based on data for this year. A 39-year macro-projection (2011-2050) that reflects the developments in terms of the stated macroeconomic variables that have taken place in the world economy since 2011 is therefore implemented to identify future baseline conditions and outcomes, assuming no climate change. In effect, the projection imposes a new macroeconomic equilibrium on the world economy with updated data. The cumulative growth rates used to construct the baseline with a projection of the

Table 1: Percentage change in macroeconomic variables in 2050 compared to the baseline year 2011, by region, under no climate change condition

Region	Agricultural land		Irrigation water	Population	Real[1] GDP	Capital [1] stock	Technological change [2]	Labor [1] force	Pasture [2] land	Natural [2] resource
	Rainfed	Irrigated								
Egypt	0.0[3]	17.4	1.7	94.5	835.3	823.3	85.82	121.1	640.7	243.6
Ethiopia	40.8	75	31.6	84.6	684	623.5	164.38	77.2	230.8	360.1
EQL Region	29.7	103.3	75	117.4	433.9	450.8	62.05	154.5	207.7	228.9
Sudan	41.7	29.5	9.2	214.9	1243.6	230	336.49	211.3	390.5	215.2
Rest of East Africa	29.7	29.5	0.1	176.4	321.4	214.5	145.79	30.9	154.5	305.1
Rest of North Africa	5.9	18.8	30.9	52.4	293.5	277.5	72.49	32.3	88.6	166.2
Rest of Sub-Saharan Africa	30.2	94.7	54.1	150.9	541.3	411.4	82.94	167.9	255.9	269
Rest of the world	-2.9	12.2	-3.7	34	190.3	169.7	61.85	32.8	60.9	75.7

Source: Own computations based on data from Nelson et al. (2010)

[1]Own computation based on data from Foure et al. (2012)

[2]Based on macro-projection simulation results

[3]Rainfed agriculture hardly exists in Egypt.

world economies from 2011 onwards are given in Table 1. The future baseline equilibrium therefore describes the world economy in 2050 with a constant, unchanged climate. The effects of climate change on Ethiopia's agriculture and economy are then evaluated relative to this updated baseline equilibrium.

In developing the future baseline, the model is first fed with projected changes in value between 2011 and 2050, for the following major macroeconomic variables: real GDP, population and supplies of rainfed land, irrigated land, irrigation water, capital, skilled and unskilled labor. To impose the projected real GDP, the endogenous real GDP variable is made exogenous by changing the model closure. This is done by swapping real GDP for factor input technological change, which is an exogenous variable in the model. Similarly, closure swap is applied to make the exogenous pasture land and natural resource endowments endogenous in implementing the baseline simulation. These closure swaps create a baseline scenario experiment that solves for the change in economy-wide factor input-technological change that is necessary to achieve the projected growth in real GDP, given the projected growth in factor supplies (endowments) and population. The original closure is then restored, making real GDP endogenous and factor inputs-technological change, pasture land and natural resources exogenous. Finally, the solution values for growth in factor input-technological change, pasture land and natural resource are added to the baseline shocks and the baseline experiment re-solved. The results of this experiment make up the baseline scenario for the world economy in 2050 under conditions of no climate change.

4.2. Climate change scenario

To estimate the economy-wide impacts of climate change on Ethiopia's agriculture and economy, climate change related effects on crop water requirements, rainfed and irrigated crop yields, as well as land use changes in irrigated and rainfed agriculture are considered. In this study, climate change impacts on agriculture in Ethiopia are assessed for two global emissions scenarios (A1 and B1), each from two global circulation models (GCM) (CSIRO[1] and MIROC[2]) in 2050. The average of CSIRO and MIROC data are considered in determining data on climate change effects for the A1 and B1 scenarios. The A1 scenario describes a future of high population growth and fast economic growth with rapid introduction of efficient technologies (IPCC 2000). The B1 scenario, on the other hand, describes a future with similar population growth as in the A1 scenario but with rapid changes in the economic structure, oriented toward a service and information economy, reduction in material intensity and the use of clean and efficient technologies (IPCC 2000). Climate change related variations in crop yield, crop land and crop water requirements are computed based on data from Nelson et al. (2010) and presented in Table 2. Using data from Nelson et al. (2010), climate change induced variations in rainfed and irrigated land endowments are estimated at -3.6 and -31.1 percent, respectively, under the A1 emissions scenario. Under the B1 emissions scenario, the estimates stand at -1.4 and -30.5 percent, respectively, for rainfed and irrigated land endowments.

1 CSIRO (Commonwealth Scientific and Industrial Research Organization): CSIRO-Mk3.0 general circulation model (Nelson et al. 2010).

2 MIROC: MIROC 3.2 medium resolution general circulation model produced by the Center for Climate System Research, University of Tokyo, the National Institute for Environmental Studies, and the Frontier Research Center for Global Change, Japan (Nelson et al. 2010).

Table 2: Percentage change in agricultural land and crop water requirements by crop, due to climate change. A comparison of 2050 to the baseline year 2011, under the two global Intergovernmental Panel on Climate Change (IPCC) emissions scenarios

Crops	Rainfed yield		Irrigated yield		Crop water requirements		Multifactor[1] productivity	
	A1 Scenario	B1 Scenario	A1 Scenario	B1 Scenario	A1 Scenario	B1 Scenario	A1 Scenario	B1 Scenario
Rice	-0.5	-0.3	-0.4	-0.2	0.0	0.0	-3.55	-2.23
Wheat	-23.5	-18.1	-20.9	-16.1	2.8	2.9	-17.08	-4.45
Other cereals	-5.1	-3.8	-4.5	-3.3	5.5	7.3	-8.65	-6.88
Other crops	-6.1	-4.6	-5.4	-4.1	5.9	8.3	-9.76	-4.52
Vegetables & fruits	-12.3	-9.4	-10.9	-8.3	12.3	10.2	-9.76	-4.52
Oilseeds	-6.1	-4.6	-5.4	-4.1	16.0	10.5	-9.76	-4.52
Sugar crops	0.8	0.9	0.8	0.9	9.7	6.5	-9.76	-4.52

Source: Own computations based on data from Ringler et al. (2010), Beyene et al. (2010) and Tubiello et al. (2006).

[1]Based on data from Roson and Sartori (2016).

The study hypothesizes that climate change modifies the availability and productivity of vital agricultural resources and impacts agricultural production, market prices and overall economic conditions in Ethiopia. More specifically, climate change related effects on crop water requirements, rainfed and irrigated crop yields as well as land use changes in irrigated and rainfed agriculture are expected to depress agricultural production and raise crop prices, resulting in declining GDP and welfare losses.

5. Simulation results

This section presents the simulation results on the effects of climate change on Ethiopia's agricultural sector and overall economy. Climate change impacts on Ethiopia's economy are assessed using several indicators including agricultural production, market prices of agricultural products, changes in land and water allocations across crops, economic growth (change in real GDP), welfare effects and returns to primary factors. The economic impacts of climate change are evaluated relative to the projected 2050 benchmark equilibrium without climate change. In assessing the impacts of climate change on agriculture, the study zooms in on seven arable farming sectors most affected by climate change.

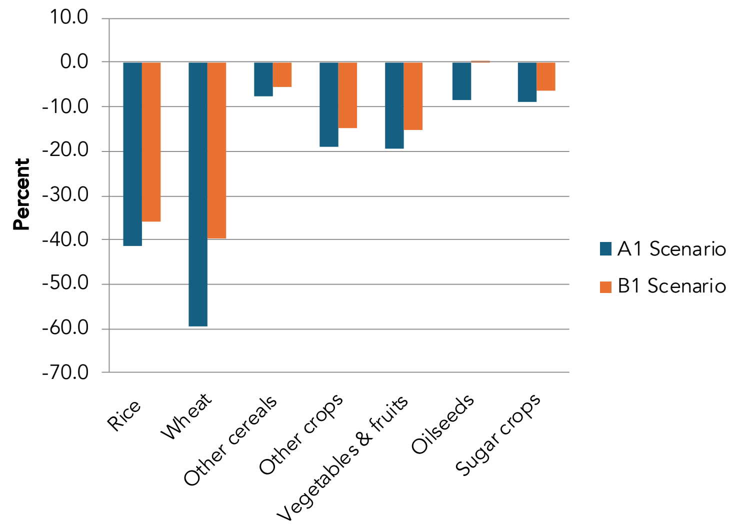
Climate change, among other things, modifies land and water endowments, that is, climate change adversely affects the availability and use of vital agricultural endowments like rainfed land, irrigated land and irrigation water. Table 3 presents the impacts of climate change on these essential agricultural resources. Results for the A1 scenario reveal that rainfed and irrigated land uses decline in all agricultural sectors by 2.5 to 39.8 percent and 11.1 to 52.3 percent, respectively. Crops that are most affected by climate change-induced declines in rainfed land are wheat (39.8 percent), rice (38.5 percent) and other crops (15.3 percent). For irrigated agriculture, climate change results in significant loss of land in all crops although the effect is more prominent for some crops including wheat (52.3 percent), rice (50.7 percent), fruits and vegetables (35.5 percent) and sugar crops (35.2 percent). Similarly, irrigation water use under this scenario decreases in all agricultural sectors by 6.3 to 48.2 percent, except in the other cereals and oilseed sectors where use of irrigation water increases by 9.7 and 29.6 percent, respectively. Results for the B1 scenario reveal similar but less prominent effects of climate change on agricultural resource use, compared to those for the A1 scenario. Under the B1 scenario, rainfed and irrigated land use fall for all crops by 0.9 to 31 percent and 8.9 to 46.3 percent, respectively. Results for irrigation water use under this scenario show a 6.9 to 35.3 percent decline in all agricultural sectors, except for other cereals and oilseeds where irrigation water use rises by 9.8 and 22.5 percent, respectively, (Table 3).

Table 3: Percentage change in land and water allocation across agricultural sectors in 2050 as a result of climate change, compared to the baseline scenario

Crop	Rainfed land		Irrigated land		Irrigation water	
	A1 Scenario	B1 Scenario	A1 Scenario	B1 Scenario	A1 Scenario	B1 Scenario
Rice	-38.5	-31.0	-50.7	-46.3	-35.7	-32.3
Wheat	-39.8	-24.6	-52.3	-41.6	-48.2	-35.3
Other cereals	-6.6	-1.4	-17.0	-16.4	9.7	9.8
Other crops	-15.3	-10.1	-29.7	-29.3	-7.5	-6.9
Vegetables & fruits	-2.5	-0.9	-35.5	-35.7	-14.3	-17.2
Oilseeds	-9.5	-1.4	-11.1	-8.9	29.6	22.5
Sugar crops	-3.0	-1.6	-35.2	-35.7	-6.3	-12.9

The impacts of climate change on land and water endowments is reflected in the levels of crop production across the country. The simulation results demonstrate that climate change leads to diminished crop production (Figure 2). Under the A1 scenario, substantial declines are observed in the production of wheat (59.5 percent), rice (41.3 percent), fruits and vegetables (19.6 percent) and other crops (19.2 percent). Production losses are relatively less prominent in other cereals (7.8 percent), oilseeds (8.6 percent) and sugar crops (8.7 percent). Similarly, production under the B1 scenario drops for wheat (39.7 percent), rice (35.8 percent), fruits and vegetables (15.3 percent) and other crops (15 percent). A relatively lower decline in production is observed in the other cereals (5.6 percent) and sugar crops (6.2 percent), while production remains more or less stable in the oilseeds sector. The fall in agricultural production is mainly due to climate change-induced declines in irrigated land use and a fall in the productivity of irrigation water and multifactor productivity.[3]

Figure 2: Percentage change in agricultural production in 2050 due to climate change, compared to the projected baseline scenario



3 Multifactor productivity refers to the productivity of all the inputs used in the production process. It measures output per unit of combined inputs and indicates the overall production efficiency of a sector or an economy (Apostolides 2008).

Changes in agricultural production inevitably influence market prices of crops. Declines in crop output due to climate change and the subsequent decreased supplies would result in higher crop market prices and vice versa. Accordingly, the simulation results for market prices of all crops show a 4 to 91.5 percent rise under the A1 scenario (Figure 3). The price surge is quite dramatic for vegetables and fruits (90.5 percent) and sugar crops (70.3 percent). Price rises are significant for wheat (37.7 percent), other crops (36.7 percent) and other cereals (21 percent), and are relatively modest for rice (13.6 percent) and oilseeds (4 percent). Similar but relatively fewer notable changes in crop prices are observed for the B1 Scenario (Figure 3). The surge in crop prices is essentially attributable to climate change-induced declines in crop production. The effects of the drop in crop production are also reflected in the international trade in crops. A substantially significant decline in crop exports ranging from 38.1 to 94.2 percent for all crops is observed under the A1 scenario (Figure 4), except for oilseeds which register a lower decline (15.8 percent). On the other hand, imports of sugar crops (276.5 percent), vegetables and fruits (178.1 percent), other crops (105.3 percent), and wheat (66.2 percent), exhibit a significant rise. The rise in imports is modest for cereals (15.4 percent), is limited for oilseeds (2.7 percent), and negative but limited for rice (-2.9 percent). Similar but slightly less pronounced results are observed for crop exports and imports under the B1 scenario (Figure 4). The rise of crop imports in the face of significant export declines will have serious repercussions for the economy which is characterized by low levels of foreign exchange.

Figure 3: Percentage change in market prices of agricultural production in 2050 due to climate change, compared to the projected baseline scenario

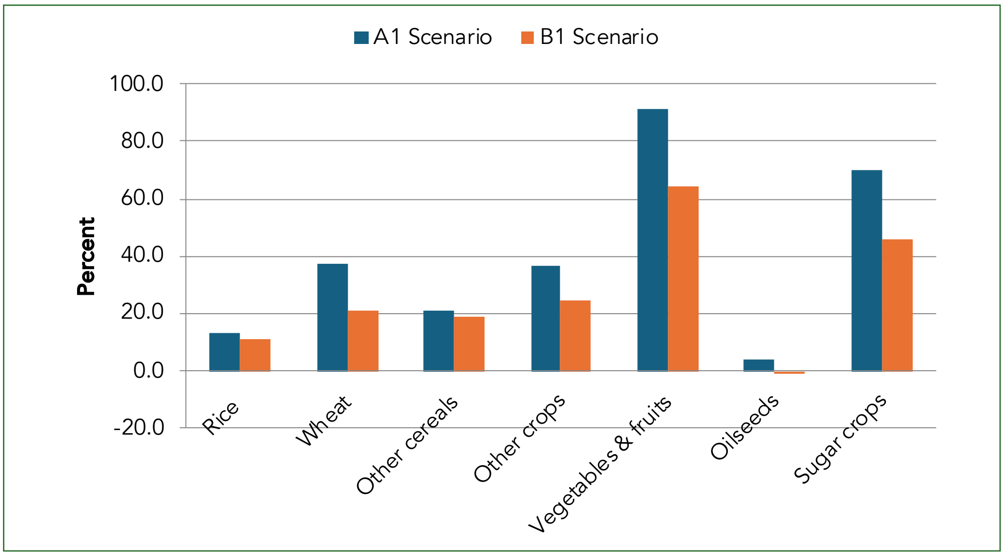
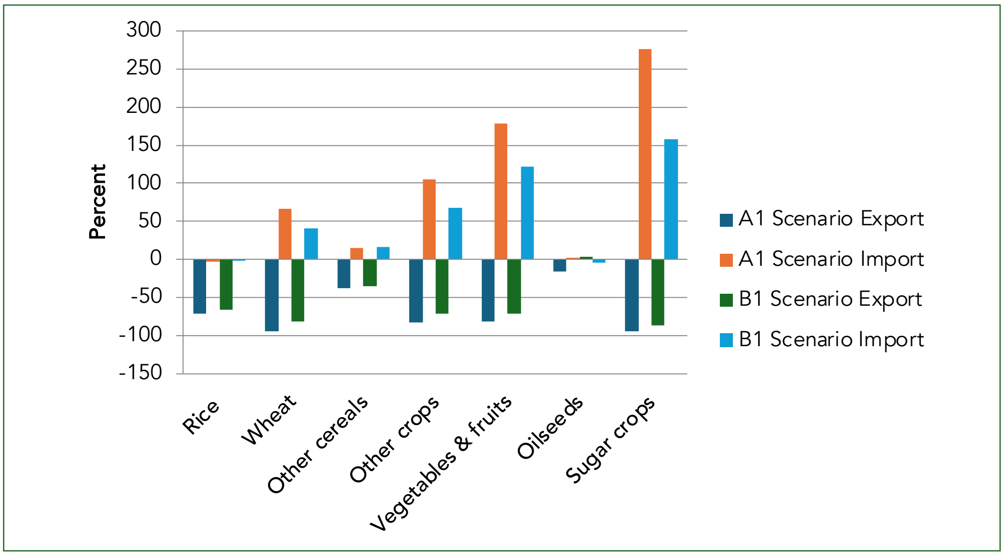


Figure 4: Percentage change in crop exports and imports in 2050 as a result of climate change, in comparison to the projected baseline scenario



The macroeconomic effects of climate change in the country as measured by change in real GDP, economic growth and welfare effects are reported in Table 4. Climate change causes a loss in real GDP amounting to US$ 18.7 billion under the A1 scenario and US$ 12.9 billion under the B1 scenario. This loss in real GDP results in 8.9 and 6.2 percent declines in economic growth, respectively. Climate change induces a similar adverse welfare effect, measured in terms of equivalent variation (EV).[4] The total welfare losses attributable to climate change in the country are about US$ 18 billion and US$ 12.1 billion, for the A1 and B1 scenarios respectively. The welfare decomposition results reveal that the losses climate change induces are mainly due to the effects of technology (68 percent) and endowment (30 percent). Climate change induced technology effect are reflected in the declining productivity of factor inputs which depresses the economy's effective endowments and productive capacities. The endowment effect is realized in the form of declining quantities of factors of production due to climate change, which degrades the economy's productive capacity.

Table 4: Change in real GDP and welfare due to climate change in 2050, relative to the predicted baseline scenario

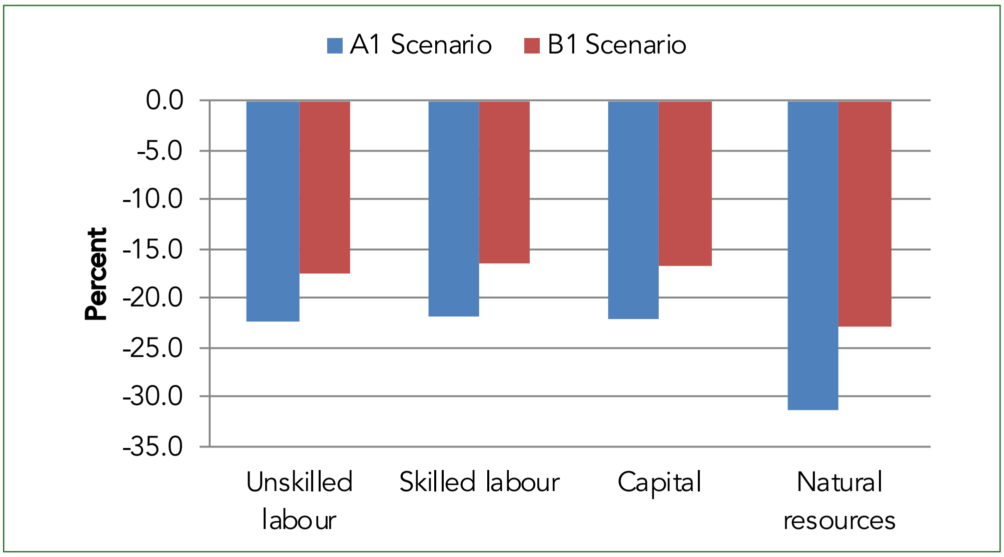
	Economic growth (%)	Real GDP (billion US$)	Welfare (billion US$)
A1 Scenario	-8.9	-18.7	-18
B1 Scenario	-6.2	-12.9	-12.1

Moreover, climate change tends to depress the real returns for primary factors including skilled and unskilled labor, capital and natural resources. Substantial declines are observed in the real returns for unskilled labor (22.4 percent), skilled labor (21.9 percent), capital (22.2 percent), and natural resources (31.3 percent) under the A1 scenario (Figure 5). Results for the B1 scenario reveal relatively lower effects, i.e., a decline of 17.5, 16.4, 16.7 and 22.9 percent, respectively, in the real returns of the resources. The real return to primary factors measures return to factors relative to the price index of consumption expenditure. The marked declines in the real return to factors will adversely affect the 'access to food' dimension of food security and further deepen Ethiopia's already precarious food security situation. More specifically, the substantial declines in real returns to unskilled labor (22.4 and 17.5 percent under the A1 and B1 scenarios respectively) indicate that climate change will further entrench poverty. Unskilled labor represents the least paid proportion of the population. The declines in returns to unskilled labor (22.4 and 17.5 percent, under the A1 and B1 scenarios respectively) are

4 Equivalent variation measures the amount of income that would have to be given to an economy before climate change so as to leave the economy as well off as it would be after climate change.

much higher than the declines in real GDP (8.9 and 6.2 percent, under the A1 and B1 scenarios respectively). This shows the significant effects climate change would have in deepening poverty in the country.

Figure 5: Percentage change in real returns to primary factors due to climate change



6. Discussion and conclusion

This study employed a multi-regional, multi-sectoral computable general equilibrium (CGE) modeling framework to assess the economy-wide impacts of climate change on Ethiopia's agriculture and economy. The effects of two exogenous climate change scenarios (A1 and B1 scenarios) are evaluated in terms of agricultural production, market prices of crops, crop imports and exports, real GDP, economic growth, welfare effects and real returns to primary factors.

The study reveals that climate change will have significant adverse effects on Ethiopia's agriculture and the overall economy. Climate change depresses agricultural production significantly resulting in a surge in crop market prices. Climate change also significantly affects the country's international trade in crops as it depresses exports and stimulates imports, thereby putting further pressure on the country's already low foreign currency reserves. Climate change would diminish the country's growth potential substantially and result in significant welfare losses. Moreover, climate change exerts significant adverse effects on real returns to primary factors. The substantial declines in real returns, especially to unskilled labor, points to climate change deepening Ethiopia's already severe poverty levels. In all cases, the adverse impacts of climate change are more pronounced for the IPCC's A1 scenario than the B1 scenario. Overall, climate change decreases the availability and productivity of the country's vital agricultural resources and degrades the productive capacities of the economy.

The results reported in this study are more or less consistent with the findings of previous CGE studies on climate change impacts on the Ethiopian economy. These CGE studies showed that climate change depresses crop production and results in GDP losses (Yalew et al. 2017; Solomon et al. 2021). This study's findings also align with previous findings which show that food production, GDP and welfare would fall on a global scale due to climate change (Calzadilla et al. 2011; Calzadilla et al. 2013a; Calzadilla et al. 2014). Results from partial equilibrium models which estimate the marginal effects of climate variables (temperature and precipitation) on crop production are not comparable to those from CGE models on climate change. Results from the two modeling approaches can however be compared qualitatively in terms of the relationship between climate change (climate variables) and crop production. In that respect, this study's findings are consistent with those from previous partial equilibrium models on climate change (Deressa 2007; Deressa and Hassan 2009; Malua 2009; Mano and Nhemachena 2006; Kabubo-Mariara and Karanja 2007) in the sense that in both cases, climate change is found to have adverse effects on agricultural production.

Given the overarching significance of agriculture in Ethiopia's economy, climate change induced shocks related to agriculture have serious implications for the entire economy depressing the prospects of economic growth and aggravating the already precarious poverty and food security situation in the country. In light of this, adaptation of the country's agriculture to climate change is imperative to protect the livelihoods of the poor and ensure food security. Adaptation measures can make significant contributions towards alleviating the adverse effects of climate change (Baylie and Fogarassy 2021) seen in its significant impacts on farm productivity and net farm revenues (Di Falco 2012). Several climate change adaptation mechanisms in Ethiopia have been proposed in different studies. These include the use of different crops or crop varieties, soil conservation, changing planting dates, irrigation (Bryan et al. 2009), planting drought tolerant and early maturing crop varieties, educating farmers and promoting livestock ownership (Deressa 2007). Similarly, Zegeye, (2018) proposed the implementation of protected area systems as well as afforestation and reforestation programs, shifts to renewable energy sources, improving energy efficiency, practicing ecological agriculture, traditional agroforestry systems and promoting the use of non-timber forest products as feasible climate change mitigation and adaptation strategies. However, farmers in Ethiopia were more likely to adapt if they had access to extension services, credit, wealth and climate information (Di Falco 2012; Bryan et al. 2009). Food aid, extension services, and information on climate change are factors that facilitate adaptation among the poorest farmers (Bryan et al. 2009). Lack of access to land, information and credit are identified as the major barriers to adaptation in Ethiopia (Bryan et al. 2009). Therefore, the government has to support adaptation measures among farmers by providing access to credit, land and climate information. Moreover, short-term efforts to combat climate change need to focus more on adaptation than mitigation given the predominantly subsistence nature of Ethiopian agriculture. The analysis of climate change mitigation and adaptation options in Ethiopia is deferred for future studies.

This study represents the first efforts to use a global CGE model to analyze the implications of climate change on Ethiopia's agriculture and economy. The study assesses the impacts of climate change in a multi-sector and multi-country CGE setting. It is based on the globally accepted GTAP database and employs relevant data in designing baseline and climate change scenarios. However, the static nature of the GTAP-W model is a limitation of the study presented here. A dynamic GTAP-W model based on the dynamic GTAP model would in theory be expected to better absorb climate change-induced shocks in the country through adjustments in the national capital stocks, such as investments in durable irrigation infrastructure. Despite the static nature of the model, the results of the current analysis demonstrate the potential risks that climate change poses to Ethiopia's economy and agricultural sector.

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8. Appendix A: Regional Aggregation

Region	Description
Egypt	Egypt
Ethiopia	Ethiopia
Sudan (pre-2011)	Sudan, including South Sudan
Equatorial Lakes Region	Democratic Republic of Congo (DRC), Uganda, Kenya, United Republic of Tanzania
Rest of East Africa	Burundi, Comoros, Djibouti, Eritrea, Mayotte, Seychelles, and Somalia
Rest of North Africa (Rnf)	Morocco, Tunisia, Rest of North Africa
Rest of Sub-Saharan Africa	Cote d'Ivoire, Senegal, Rest of WAEMU, Ghana, Nigeria, Rest of ECOWAS, Cameroon, Rest of CAEMC, Rest of SADC, Rest of COMESA, Botswana, South Africa, Rest of South African CU, Madagascar, Malawi, Mauritius, Mozambique, Zambia, Zimbabwe, Rest of Sub-Saharan Africa
Rest of the World	Oceania, East Asia, Southeast Asia, South Asia, North America, Latin America, European Union 25, Rest of Europe, Middle East,

WAEMU: West African Economic and Monetary Union

ECOWAS: Economic Community of West African States

CAEMC: Central African Economic and Monetary Community

SADC: South African Development Community

COMESA: Common Market for Eastern and Southern Africa

CU: Customs Union

9. Appendix B: Sectoral Aggregation

Sector	Detail Description
I. Agricultural Sectors	
Paddy rice	paddy
Wheat	wheat
Other cereals	Cereal grains not elsewhere classified (nec),
Other crops	Plant-based fibers; crops nec; processed rice,
Vegetables and fruits	Vegetables, fruit, nuts
Oilseeds	Oil seeds
Sugar crops	Sugar cane, sugar beet
Livestock and meat products	Cattle, sheep, goats, horses; animal products nec; raw milk; wool, silk-worm, cocoons; meat: cattle, sheep, goats, horses; meat products nec;

II. Non-agricultural sectors	
Coal	Coal
Crude	Oil
Gas	Gas; gas manufacturing, distribution
Petroleum	Petroleum, coal products
Processed food	Vegetable oils and fats; dairy products; sugar; food products nec; beverages and tobacco products
Extraction	Forestry fishing
Manufacturing	Minerals nec; textiles; wearing apparel; leather products; wood products; paper products, publishing; chemical, rubber, plastic prods; mineral products nec; ferrous metals; metals nec; metal products; motor vehicles and parts; transport equipment nec; electronic equipment; machinery and equipment nec; manufactures nec;
Water	Water
Services	Construction; trade; transport nec; sea transport; air transport; communication; financial services nec; insurance; business services nec; recreation and other services; public administration, defense, health, education; dwellings
Ely_hydro	Hydro base load, hydro peak load
Ely_fossil	Coal-based load, gas-based load, oil-based load, gas peak load, oil peak load
Ely_other	Nuclear base load, wind base load, other base load, solar peak load

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