Economic Impacts of Regional Nuclear War Due to Climatic Effects on Agriculture

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Abstract

Natural and anthropogenic aerosols in the stratosphere can change surface climate and have profound impacts on agriculture and world food trade. Large impacts may even produce famine. We focus on the impacts of a regional nuclear war, in which 5 Tg soot would be injected into the stratosphere in the subtropics, which could be produced by a war between two new nuclear states using much less than 1% of the global nuclear arsenal, and which would create climate change unprecedented in recorded human history. Using input from global gridded agricultural simulation models, which calculate the change in production of major crops in each country during a 10-year period following the soot injection, we use the computable general equilibrium model to evaluate the impacts on regional prices of food. To test the model, we generate a 20% reduction in food production (a homogenous shock on all commodities) from 2021 to 2030, and calculate the economic response for the following 10 years. Globally, the aggregated nominal outputs of five major crops have notable reductions by 11.3%, 15.5%, 9.7%, 9.2% and 10% for corn, rice, soybean, sugar and wheat, respectively, over 19 regions. And the aggregated output on the top level of the nest of production block directly impacts the value added bundle in the second level of the nest. The aggregated unweighted demand of value added bundle is suffering an average reduction of 7.0%, 8.7%, 6.4%, 6.4% and 6.7% on corn, rice, soybean, sugar and wheat respectively over 19 regions. Furthermore, these two indicators significantly affect the trade market, such as the sum of domestic and imported demand. The noteworthy reductions are estimating by 11.1%, 15.4%, 9.2%, 9.2% and 9.8% on average with respect to corn, rice, soybean, sugar and wheat. Finally, the reductions of output and demand on the top level of the production block indeed show its impact on the aggregate factor price index, such as the wage index for skilled and unskilled labor. The former one has 2.9% raise in wage level, while the latter one has only

0.2% raise. Different regions with different level of effects on demand is due to different elasticities of demand reflecting different sustainability under environmental crisis from nuclear threat.

1. Introduction

1.1 Nuclear War Scenario

In developing the scenarios, we work through climate, crop, and economic models and quantify the economic effect of these forcing factors, and discuss the implications of the climatic impact of nuclear war for the general public and the poor, within and between nations. The coupling of climate, biophysical, and economic models is used to quantify the effect of changes in climate forcing on agricultural systems including trade and food security, and investigate the food-mediated implications for the distribution of wealth. We evaluate a variety of potential responses to the changes in agricultural markets, including behavioral changes such as migration and technological changes. The analysis compares the socioeconomic outcomes through a multimarket model and contrasts these outcomes with a computable general equilibrium model, an extension of the Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) Model, to better understand the implications of a nuclear event, with the differences between the two models attributed to economy-wide spillover effects.

A regional nuclear war is likely to start regional forest fires, releasing toxic air and generating dark smoke clouds over the regional war zone [*Crutzen and Birks,* 1982]. *Turco et al*. [1983] indicated that more soot would be produced from burning cities and industrial areas, which would rise into the stratosphere where it would spread to the entire Earth and result in large global climatic consequences described as “nuclear winter.” The world would be challenged by potential indirect effects much larger than direct effects of nuclear war. The direct effects might be the death of hundreds of millions innocent people in combat fields and nearby, while the indirect effects might be out of control by resulting in collapse of global agriculture and starvation of billions of people in areas far beyond the warring parties.

About 5 Tg of black carbon would be produced of a regional nuclear war between India and Pakistan under the assumption that each side will detonate 50 15 kt weapons [*Toon et al.*, 2007]. Winds will drift those soot into the stratosphere where the darken smoke clouds will significantly impact global climate by spreading, so that it will produce a sharp drop in surface temperature and cause intense heating in stratosphere. *Robock et al.* [2007a] and *Mills et al.* [2014] found long-lasting impacts from this regional nuclear war although the papers did not explore how this would affect agriculture production, water resources, and ocean biosphere change in response to the climatic disruption and enhanced ultraviolet radiation from nuclear war. So far, this 5 Tg regional nuclear war has been evaluated by investigating two crops in U.S. (soybean and corn) using Agro-IBIS, a dynamic agroecosystem model [*Ozdogan et al.*, 2013], and three crops in China (rice, wheat and corn) using Decision Support System for Agrotechnology Transfer agriculture simulation model with output from three climate models [*Xia e al*, 2015].

The purpose of this paper is to investigate the economic impacts of those changes using a dynamic economic model, ENVISAGE with the output from a climate model, Community Land Model – Crop (CLM-Crop). In the ENVISAGE model, this paper focuses on the production block on crops by introducing a 20% shock (yield reduction) in 2021, the initial year of the regional nuclear war, for five crops including corn, rice, soybean, sugar and wheat.

1.2 Climate Model on India and Pakistan Scenario – CLM5crop

The Community Earth System Model (CESM) of the National Center for Atmospheric Research (NCAR) coupled the Community Land Model version 3 (Oleson et al., 2004) with interactive crop management parameterization from AgroIBIS (Integrated Biosphere Simulator) (*Kucharik et al.*, 2000; *Kucharik and Brye*, 2003). It went through couple development stages, and the most updated version is with the Community Land Model version 5 (CLM5crop).

Active crops in CLM5crop are cotton, maize, rice, soybean, sugarcane and wheat. The crop model uses the same physiology as the natural vegetation, though uses difference crop-specific parameter values, phenology, allocation, fertilizer and irrigation management. Three phenology phases are considered in crop simulation including planting, leaf emergence and grain fill.

Crops are planted if the growing degree-days (GDD) with a specific base temperature for each crop meet the minimum requirement, and the exact planting date is determined by the 10-day running mean of 2 m air temperature and minimum temperature. Once the crop is planted, the model will assign 3 g C/m^2 as well as an equivalent amount of nitrogen to the seed pool. When the GDD of soil temperature at a depth of 5 cm reaches 1% to 5% of the GDD for the crop to reach vegetative and physiological maturity, the planted crop starts leaf emergence – all seed carbon is transferred to leaf carbon, which leads to an increase in Leaf Area Index (LAI). There are two ways to trigger the third phase, grain fill. The first is that the LAI reaches the maximum, and the second one is that GDD of 2 m air temperature reaches 40% to 65% of the GDD for the crop to reach vegetative and physiological maturity. Finally, harvest occurs when the crop reaches maturity by means of GDD of 2 m air temperature reaches 100% of the GDD maturity. In this nuclear war simulation, CO_2 concentration is fixed as 360 ppm to exclude CO_2

fertilization effects, and the fertilizer usage is fixed at 2000. Irrigation water is from river water storage, which is applied based on crop water demand over the irrigation area.

1.3 Economy Model of the India and Pakistan Scenario – ENVISAGE

The ENVISAGE Model is designed to analyze a variety of issues related to the economics of climate change including baseline emissions of CO_2 and other greenhouse gases, impacts of climate change on the economy, adaptation by economic agents to climate change, greenhouse gas mitigation policies of taxes, cap and trade, the role of land use in future emissions and mitigation, and the distributional consequences of climate change impacts, adaptation and mitigation at both the national and household level. ENVISAGE is designed to be flexible in terms of its dimensions. It divides the world into 120 countries and 20 region-based aggregations. The database divides global production into 57 sectors with extensive details for agriculture activity, food trade and energy production.

This paper focuses on the climatic and economic responses from the regional nuclear war between India and Pakistan. In our ENVISAGE model, commodities are separated into 10 categories, including grains and crops, processed food, livestock and meat products, mining and extraction, textiles and clothing, light manufacturing, heavy manufacturing, utilities and construction, transport and communication, and other services. Based on the fact that Asia is the biggest grain and crop production area, we disaggregate the category of grains and crops into 8 specific classes including maize, rice, wheat, soybean, vegetables and fruits, sugar cane and beet, plant-based fibers and all other crops. Therefore, a total of 17 commodities complete the disaggregation. In the original set of regions, 10 majority regions are split including Oceania, East Asia, Southeast Asia, South Asia, North America, Latin America, European Union 28, Middle East and North Africa, Sub-Saharan Africa, and the rest of the world. Based on our India-Pakistan scenario, 7 countries which are either biggest production in majority grains or significantly direct-impact country from India and Pakistan war are listed out including India, Pakistan, China, Korea, USA, Brazil and Argentina. To further distinguish Asian effect, East Asia and rest of world are splitting into high income East Asia and developing East Asia and rest of world in Europe and rest of world in Central Asia respectively. Therefore, there are total 19 regions in this India-Pakistan economy model disaggregated including China, Korea, USA, India, Pakistan, Brazil, Argentina, Australia and New Zealand (Oceania), High-income East Asia (HEastAsia), Low-income East Asia (DEastAsia), Southeast Asia (SEAsia), South Asia (SouthAsia), North America (NAmerica), Latin America (LatinAmer), 28 countries in European Union (EU28), Middle East and North Africa (MENA), Sub-Saharan Africa (SSA), Rest of world in Europe (RowEU) and Rest of world in Central Asia (RowCA) with acronyms used in the rest of the paper. In the appendix, the model construction is explained in detail.

2. Shock on Production Yields

2.1 Mechanism of weather inputs generating from AgMERRA

Robock et al. (2007a) started a regional nuclear war simulation using National Aeronautics and Space Administration Goddard Institute for Space Studies (GISS) ModelE. The simulated regional nuclear war between India and Pakistan is using 100 Hiroshima-size nuclear bombs. According to the calculation by *Toon et al.* (2007), such a conflict would generate about 5 Tg of black carbon aerosol particles injecting into the upper troposphere.

To simulate regional nuclear war impact on global agriculture, perturbed daily weather inputs generated by delta method are used to force agriculture models. First, crop models use

AgMERRA 1980-2010 (*Ruane et al.*, 2015) as the weather inputs for the control simulation. The equations of calculating monthly anomaly of surface temperature, precipitation and surface downwelling solar radiation from the climate model output are written by the following definitions of variables.

Define af is Anomaly Forcing, nw is Nuclear War output, con is the control run; T is monthly temperature, Pr is monthly precipitation, and $RSDS$ is monthly downwelling solar radiation; j is year after the nuclear event, and i is month.

$$afT_{ij} = nwT_{ij} - \overline{conT}_i$$

$$afTmax_{ij} = nwTmax_{ij} - \overline{conT}max_i$$

$$afTmin_{ij} = nwTmin_{ij} - \overline{conT}min_i$$

$$afPr_{ij} = nwPr_{ij}/\overline{conPr}_i$$

$$afRSDS_{ij} = nwRSDS_{ij}/\overline{conRSDS}_i$$

For surface temperature, the monthly difference is uniformly added between a regional nuclear war and the average control run of climate model to daily AgMERRA temperature. For precipitation and solar radiation, the monthly ratio of a regional nuclear war and the average control run is calculated, then daily AgMERRA precipitation and solar radiation are changed by that ratio on each day. Precipitation ratio might be extremely large when the values in the control run is small, and value 5 is the maximum ratio. In addition, if precipitation in the averaged control is zero, the ratio at that grid cell is set to be 1. Each monthly anomaly forcing is applied to 31 years of AgMERRA corresponding months. For example, anomaly forcing of January for the first year after a regional nuclear war will be applied to 31 Januaries in the AgMERRA data set. In crop model simulation, CO_2 concentration is fixed as 360 ppm to exclude the CO_2 fertilization effect, fertilizer applied and seeds are not changing, and planting area is fixed.

2.2 Shock parameter in ENVISAGE model

On the first step of this paper, we only consider the global yield impact which is affected by the precipitation, solar redaction and contamination of source land. Once the nuclear war is happening, large carbon emission and redaction will contaminate the land and cause less solar redaction and precipitation. Thus, we have less inputs for the output of crops, therefore, in the economic model, we can shock the input specific technological change parameter λ^{XP} to reflect the climate model. This is reasonable when we only consider to shock one production related parameter.

2.3 Shock on production of 5 major crops

2.3.1 20% Shock on five crops from ENVISAGE model

Under the economic globalization, the world's economy is ever strongly interacted. A 20% shock on five major crops is reasonable to detect as a comparison with the dynamic shock from the CLM-crop model. We assume the nuclear event takes place in 2020, and this event affects crop production through nuclear winter from 2021 to 2030. The first one is to continue running the baseline without shock from 2021 to 2030 so called business as usual scenario; while as for the second one, a 20% homogeneous shock is introduced since 2021, the initial year of the regional nuclear war. The variable of total domestic supply indicates the response of production countries to the domestic markets after the nuclear war.

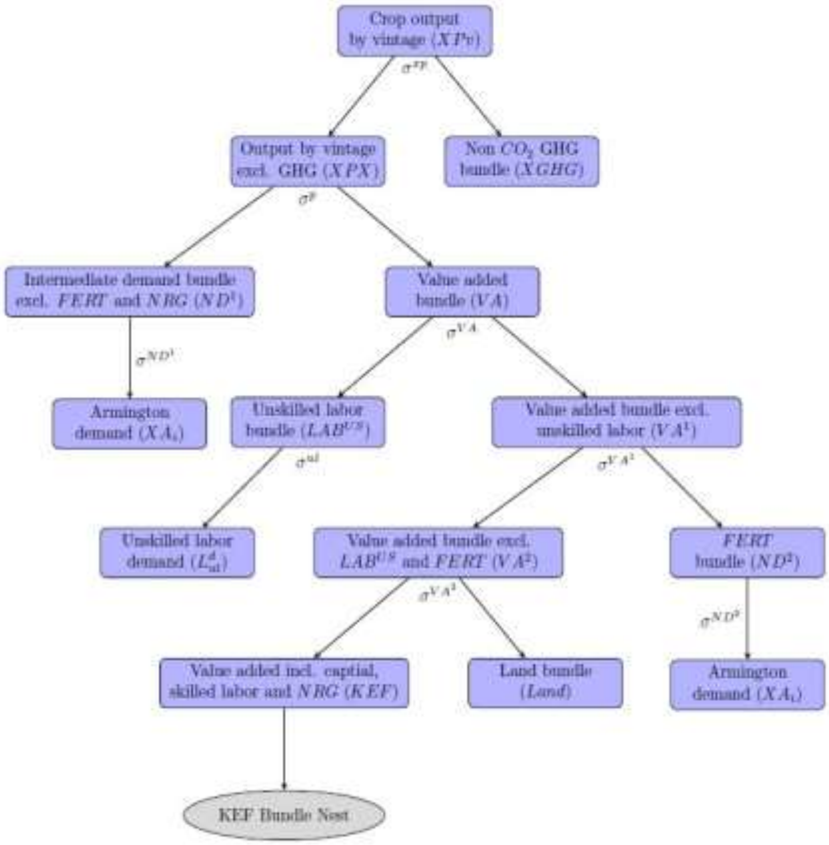

Figure 1. Crop Production Nest: the top level CES nest represents the combination of output, XPX, with a bundle of non-CO_2 greenhouse gas (GHG) emissions, $XGHG$. The second level nest decomposes aggregate production net of the GHG bundle into two bundles, ND^1 and VA. The third level nest, KEF, represents the nested combination of capital, skilled labor, energy and natural resource factors.

Figure 1 shows a nested constant elasticity of substitution (CES) crops structure, a standard in general applied equilibrium models. Each nest is reproduced for each vintage. The purpose of using CES nests it to replicate the substitution and complementarity relations across all of the inputs. And the first-step results describing in this paper are from all three levels including aggregated output, value added bundle, and trade taxes from five crops.

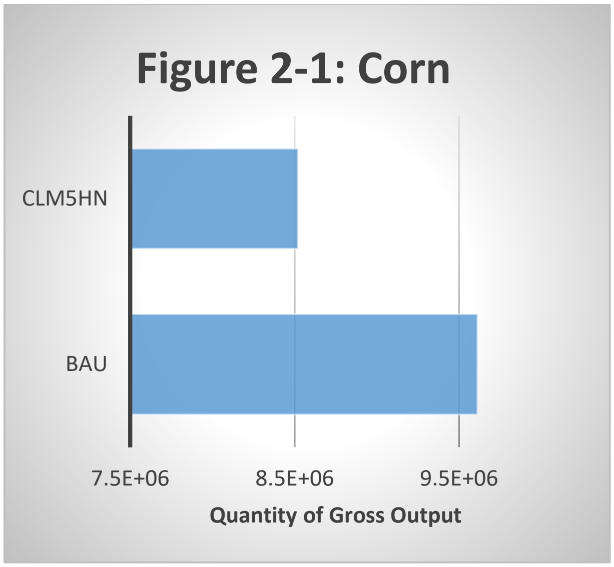

Figure 2-1: Corn

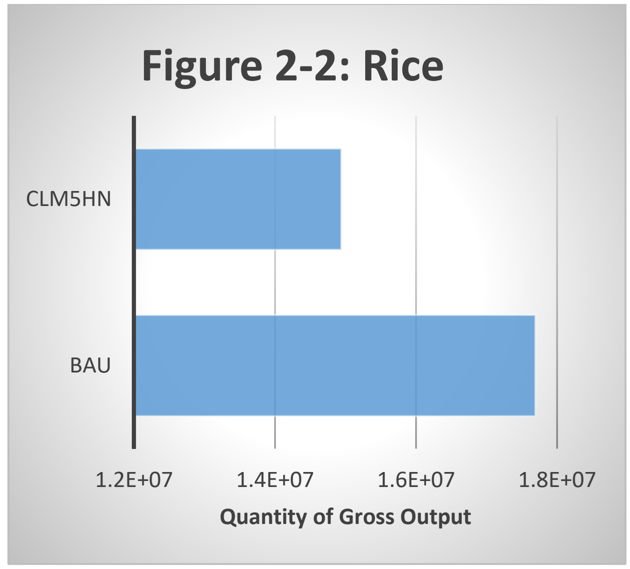

Figure 2-2: Rice

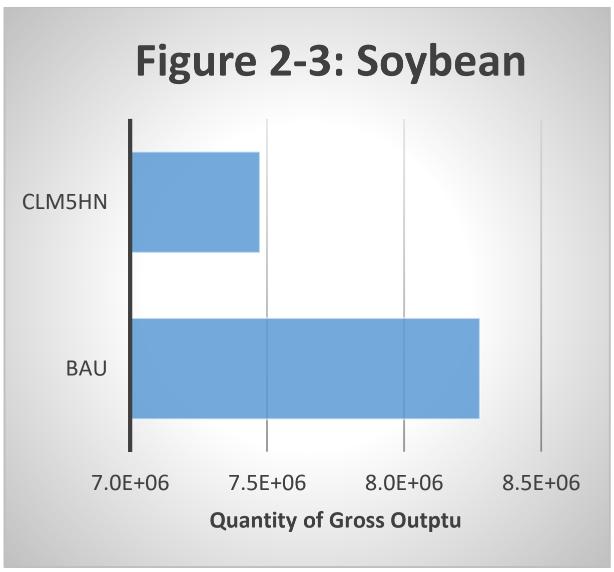

Figure 2-3: Soybean

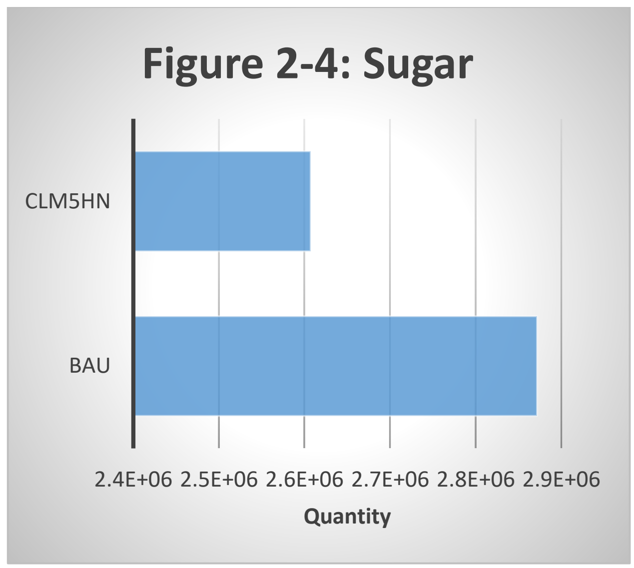

Figure 2-4: Sugar

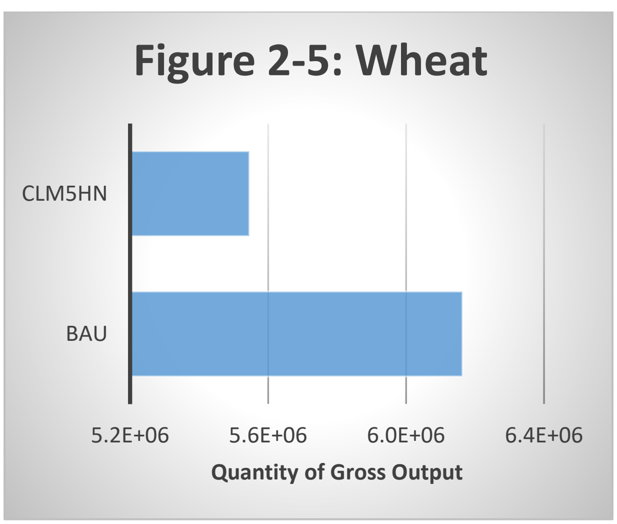

Figure 2-5: Wheat

Figure 2: Gross Output of Five Major Crops: the aggregated output of each crop including corn, rice, soybean, sugar and wheat under the 20% shock running from 2021 to 2030 over 19 regions. There are two bars for each nest figure, CLM5HN means the 20% homogeneous shock on five major crops running on ENVISAGE with output from CLM5crop, BaU means the business as usual (no shock) on ENVISAGE with output from CLM5crop.

Figure 2 shows the total nominal outputs of production on five major crop from 19 regions, which is the top level of the crop production block. The model indicates an average 11.3%, 15.5%, 9.7%, 9.2% and 10.0% reduction on corn, rice, soybean, sugar and wheat respectively in ten years from 2021. Based on the fact of the most production countries among five crops, some specific regions are listing out independent to analyze in details.

For corn, the first five biggest production countries are USA, China, Brazil, India and Argentina. The aggregated nominal output of five countries has 13.0% reduction, and the decreasing level is larger than the level over 19 regions. Respectively, the reductions on corn production on five countries are 9.6%, 16.7%, 9.8%, 10.2% and 10.2%.

For rice, the first five biggest production countries are India, China, Indonesia (SEAsia), Bangladesh (SouthAsia) and Thailand (SEAsia). So four regions including India, China, SEAsia and SouthAsia are listed out. The aggregated nominal output of four regions are suffering 16.4% reduction, and the decreasing level is server than the overall level. Respectively, the reductions on rice production on four regions are 13.9%, 18.0%, 15.6% and 14.2%.

For soybean, the first five biggest production countries are USA, Brazil, Argentina, China and India. The aggregated nominal output of five countries has 9.8% reduction, and the decreasing level is larger than the level over 19 regions. Respectively, the reductions on soybean production on five countries are 10.1%, 11.8%, 10.5%, 7.1% and 10.1%.

For sugar, the first five biggest production countries are Brazil, India, China, Thailand (SEAsia) and Pakistan. So five regions including Brazil, India, China, SEAsia and Pakistan are listed out. The aggregated nominal output of five regions are suffering 9.0% reduction, and the decreasing level is about the same as the overall level. Respectively, the reductions on sugar production on five regions are 8.6%, 9.5%, 8.8%, 9.3% and 9.2%.

For wheat, the first five biggest production countries are China, India, USA, France (EU28) and Pakistan. So five regions including China, India, USA, EU28 and Pakistan are listed out. The aggregated nominal output of five regions are suffering 10.0% reduction, and the decreasing level is about the same as the overall level. Respectively, the reductions on wheat production on five regions are 11.3%, 8.3%, 9.0%, 10.8% and 9.6%.

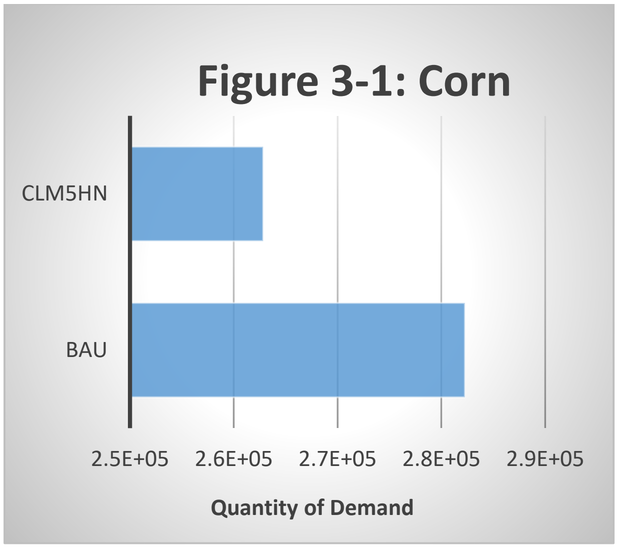
Figure 3-1: Corn
CLM5HN
BAU
2.5E+05
2.6E+05
2.7E+05
2.8E+05
2.9E+05
Quantity of Demand

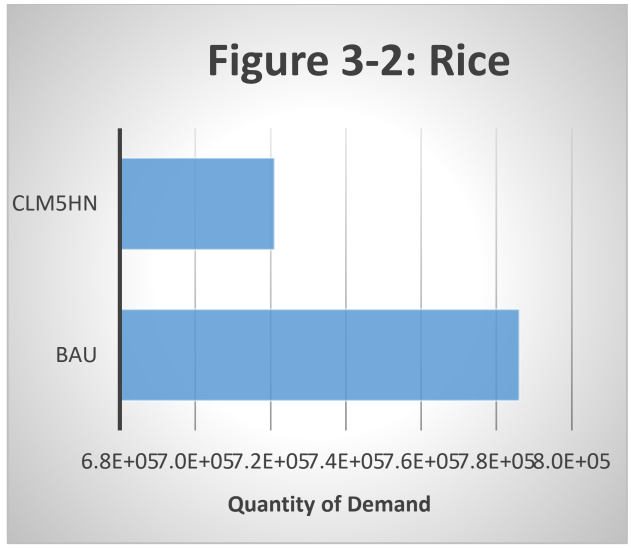
Figure 3-2: Rice
CLM5HN
BAU
6.8E+05
7.0E+05
7.2E+05
7.4E+05
7.6E+05
7.8E+05
8.0E+05
Quantity of Demand

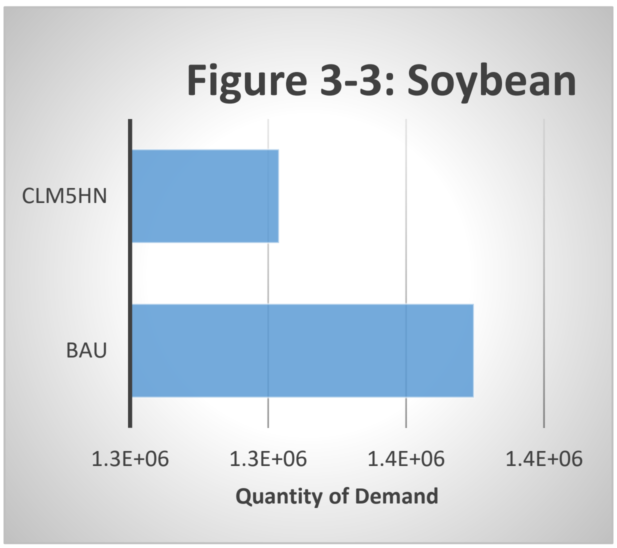
Figure 3-3: Soybean
CLM5HN
BAU
1.3E+06
1.3E+06
1.4E+06
1.4E+06
Quantity of Demand

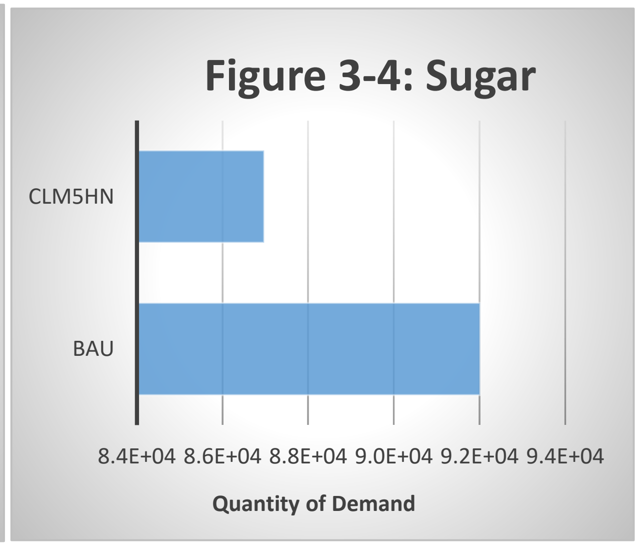
Figure 3-4: Sugar
CLM5HN
BAU
8.4E+04
8.6E+04
8.8E+04
9.0E+04
9.2E+04
9.4E+04
Quantity of Demand

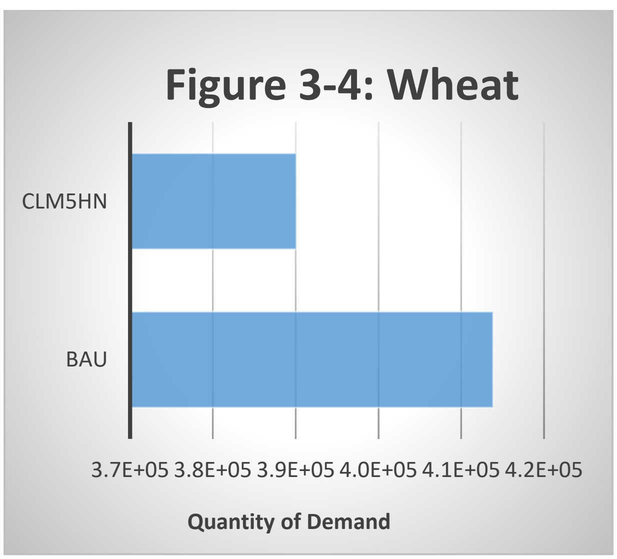
Figure 3-4: Wheat
CLM5HN
BAU
3.7E+05
3.8E+05
3.9E+05
4.0E+05
4.1E+05
4.2E+05
Quantity of Demand

Figure 3: Demand of Five Crops on Value Added Bundle: the aggregated demand of each crop including corn, rice, soybean, sugar and wheat under the 20% shock running from 2021 to 2030 over 19 regions. There are two bars for each nest figure, CLM5HN means the 20% homogeneous shock on five major crops running on ENVISAGE with output from CLM5crop, BaU means the business as usual (no shock) on ENVISAGE with output from CLM5crop.

Figure 3 shows the demand of value added bundle on five major crop from 19 regions, which is the second level of the crop production block. The model calculates an average 7.0%, 8.7%, 6.4%, 6.4% and 6.7% reduction of demand on corn, rice, soybean, sugar and wheat respectively in ten years. The second level nest decomposes aggregate production net of the GHG bundle into two bundles including all intermediate goods except energy goods and value added (VA) bundle. The VA bundle contains all factors of production, the energy goods and activity-specific goods.

For corn, the first five biggest production countries are USA, China, Brazil, India and Argentina. The aggregated demand of five countries has 7.8% reduction, and the decreasing level is larger than the level over 19 regions. Respectively, the reductions of demand on corn production on five countries are 6.4%, 9.8%, 7.3%, 6.1% and 6.9%.

For rice, the four most production regions are India, China, SEAsia and SouthAsia. The aggregated demand of four regions are suffering 9.0% reduction, and the decreasing level is server than the overall level. Respectively, the reductions on rice production on four regions are 8.4%, 10.5%, 7.5% and 8.3%.

For soybean, the first five biggest production countries are USA, Brazil, Argentina, China and India. The aggregated demand of five countries has 6.4% reduction, and the decreasing level is about the same as the overall level. Respectively, the reductions of demand on soybean production on five countries are 6.6%, 9.5%, 7.4%, 4.6% and 5.1%.

For sugar, the first five regions including Brazil, India, China, SEAsia and Pakistan are listed out. The aggregated demand of five regions are suffering 6.2% reduction, and the decreasing level is about the same as the overall level. Respectively, the reductions of demand on sugar production on five regions are 6.8%, 5.1%, 6.5%, 5.6% and 5.5%.

For wheat, the first five regions including China, India, USA, EU28 and Pakistan are listed out. The aggregated demand of five regions are suffering 6.5% reduction, and the decreasing level is about the same as the overall level. Respectively, the reductions of demand on wheat production on five regions are 7.5%, 4.9%, 5.5%, 8.1% and 5.7%.

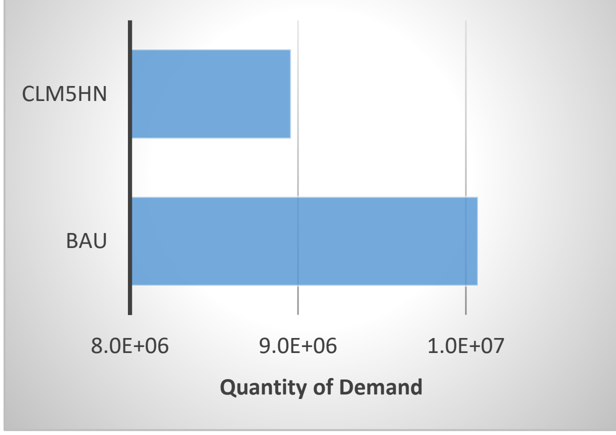

Figure 4-1: Corn

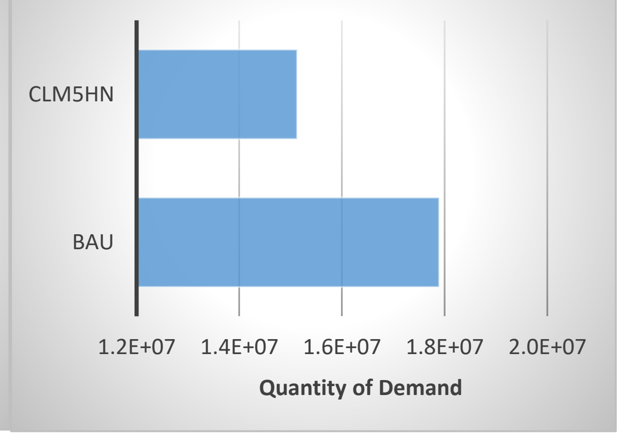

Figure 4-2: Rice

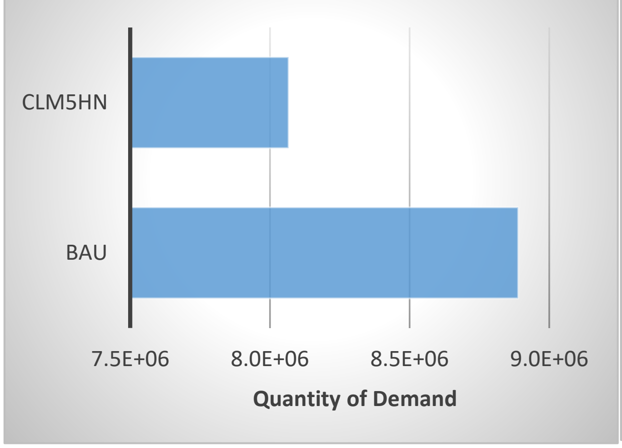

Figure 4-3: Soybean

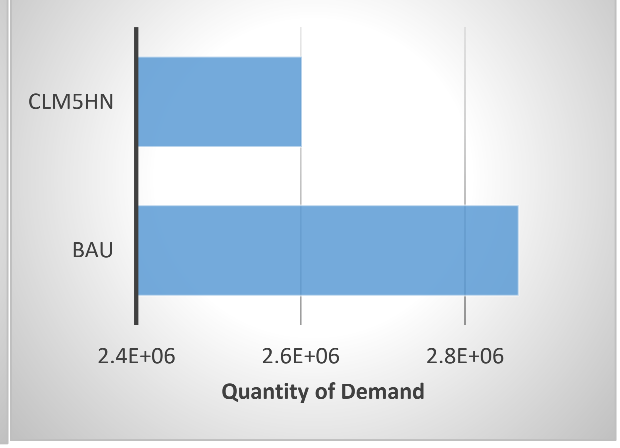

Figure 4-4: Sugar

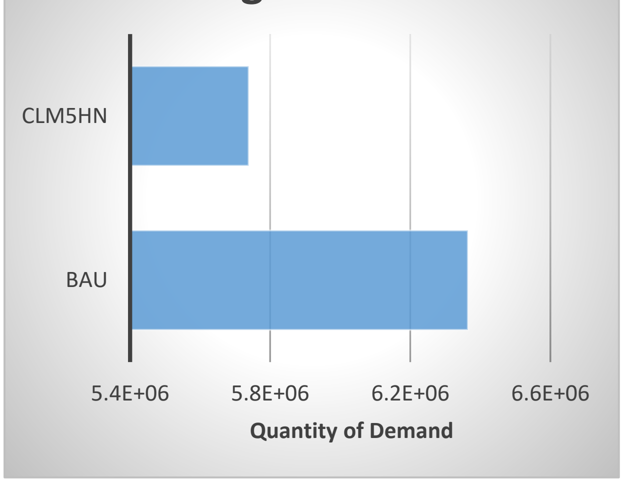

Figure 4-5: Wheat

Figure 4: Domestic and Imported Demand on Trade Market: the domestic and imported demand from five crops including corn, rice, soybean, sugar and wheat under the 20% shock running from 2021 to 2030 over 19 regions. There are two bars for each nest figure, CLM5HN means the 20% homogeneous shock on five major crops running on ENVISAGE with output from CLM5crop, BaU means the business as usual (no shock) on ENVISAGE model.

Figure 4 shows the domestic and imported demand on five major crop from 19 regions, which is in the bottom level of the crop production block. The model estimates an average 11.1%, 15.4%, 9.2%, 9.2% and 9.8% reduction on corn, rice, soybean, sugar and wheat respectively in ten years. Export and Import are playing important role in revenues especially for countries with rich resources such as petroleum and agricultural products. In the sense of supply and demand, export and import can also reflect the global responses to the regional nuclear war.

For corn, the first five biggest production countries are USA, China, Brazil, India and Argentina. Their aggregated domestic and imported demand have 13.4% reduction, and the decreasing level is larger than the level over 19 regions. Respectively, the reductions of demand on corn activity for five countries are 9.6%, 16.6%, 10.0%, 10.4% and 10.2%.

For rice, the four most production regions are India, China, SEAsia and SouthAsia. While, their aggregated domestic and imported demand are suffering 16.6% reduction, and the decreasing level is server than the overall level. Respectively, the reductions of demand on rice activity for four regions are 14.0%, 18.1%, 16.2% and 14.2%.

For soybean, the first five biggest production countries are USA, Brazil, Argentina, China and India. The aggregated domestic and imported demand of five countries have 9.3% reduction, and the decreasing level is about the same as the overall level. Respectively, the reductions of demand on soybean activity for five countries are 11.1%, 9.5%, 8.3%, 8.7% and 10.4%.

For sugar, the first five regions including Brazil, India, China, SEAsia and Pakistan are listed out. The aggregated domestic and imported demand of five regions are suffering 9.0% reduction, and the decreasing level is about the same as the overall level. Respectively, the reductions of demand on sugar activity on five regions are 8.6%, 9.5%, 8.8%, 9.3% and 9.2%.

For wheat, the first five regions including China, India, USA, EU28 and Pakistan are listed out. The aggregated domestic and imported demand of five regions are suffering 10.0% reduction, and the decreasing level is about the same as the overall level. Respectively, the reductions of demand on wheat activity on five regions are 11.3%, 8.3%, 10.9%, 9.7% and 9.3%.

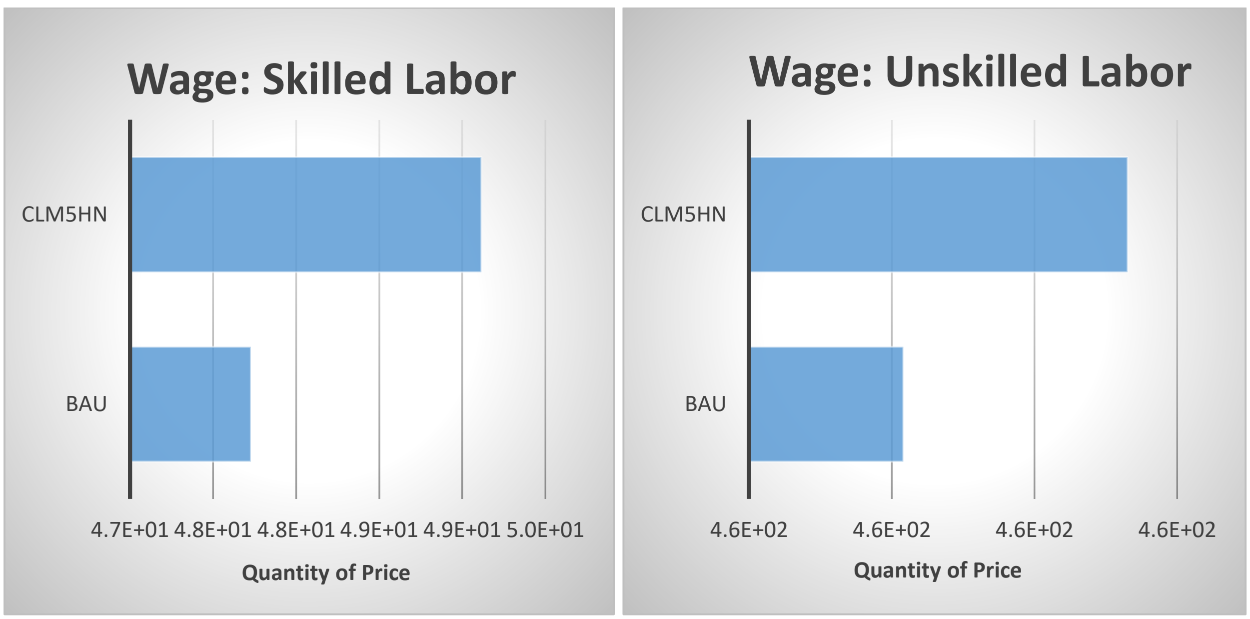

Figure 5: Aggregate Factor Price: wages identified by skilled and unskilled Labor. CLM5HN means the 20% homogeneous shock on five major crops running on ENVISAGE with output from CLM5crop, BaU means the business as usual (no shock) on ENVISAGE with output from CLM5crop. The quantity of price index is the total wage index for 19 regions.

Under the assumption of standard constant elasticity of transformation (CET), the price index is identical to the average price, where the average price is the summation of the price of land bundle and the price of demand for intermediate land bundle. Figure 5 shows the differences of wages on skilled and unskilled labor. Over 19 regions, the raise of wages on skilled labor is 2.9%, and the raise of wages on unskilled labor is only 0.2%. The quantity of price implies that the amount of needs on unskilled labor is still larger than the needs on skilled labor. While, the wage increase level for skilled labor is almost 15 times than unskilled labor.

2.3.2 Results Explanations

The total nominal output of production has notable reduction simply because the technology parameters for five crops are downgraded under 20% homogeneous shock. Given the same amount of inputs, less advanced technology is able to produce less amount of outputs. This is the key idea to explain the situation of the technology during the nuclear winter. Thus, all 19 regions are suffering significant reductions on production of five major crops. Different regions have different effects on the same crop, while the same region has different effects on different crops. It is due to the different initial values of technology parameters for different regions. In different regions, different climates and cultures in different regions results in different technology parameters for the same crop, and different crops requires different inputs also result in different technology parameters in the same region. For example, rice will be resulting better productions in unit input if the climate is better, although China has larger productions than Indonesia, rice production in China is suffering server reductions than in Indonesia because of different climate conditions. Indonesia has more sunlight and water than China, thus China is more sensitive on rice production in climate change. Also, China produces more rice than soybean because of the cultures, thus the technology parameter for rice is larger than it for soybean. Therefore, the reduction percentage for rice is larger than it for soybean.

The demand of value added bundle is affecting by the income elasticity of demand. Different countries have different income elasticity of demand based on different economic levels. In the ENVISAGE model, country with higher economic level has lower income elasticity of demand, thus its sustainability under economic attack is much stronger. For instance, USA has lower income elasticity of demand than China in the ENVISAGE model, which can also be proved from the results of 20% homogeneous shock. For three different crops including corn, soybean and wheat, the shock levels of demand of value added bundle for China (USA) are 9.8% (6.4%), 4.6% (6.6%) and 7.5% (5.5%). USA has two of them in lower reductions and lower reductions on average. Meanwhile, the demand is also affected by the elasticity of substitutions. USA is the country with largest production of corn in the world, the demand of soybean may shift to the demand of corn by the high elasticity of substitution between corn and soybean due to the lower price change in corn. While, for the aspect of trade, the demand of domestic and imported in trade market is highly impacted from the domestic demands on large production countries. As the results from the model, the reductions of the demand in global trade market are much server than the demand of value added bundle in domestic market. Trade gate will be significantly destroyed due to the reductions of the production.

Finally, our model indicates the wage level fluctuation on skilled and unskilled labors. Skilled labor is more popular than unskilled labor. And 15 times difference under 20% homogeneous shock may lead to an even worse situation in labor market in the real degradation in technology is worse than 20%.

3. Conclusions

A 20% homogeneous shock only on five major crops results in more than 10% reductions on average for each crop followed by server attack on the global trade gate and huge difference in wages for different skilled populations. It is believed that a regional nuclear war will definitely cause more damage in more areas not only for five major crops. Considering the current income gap between and rich and the poor, regional nuclear war will not only lead the environmental and economic catastrophes directly but also the culture disaster indirectly. This paper is showing the first step of the research for the global economic impact from the regional nuclear war, and more results will be presented in the future.

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Appendix A: Model Specification

A.1 Model Dimensions

The model defines all variables and equations as set-based indices as run-time when the data is imported. In the demand block the key dimension is the number of the Armington agents indexed by aa. The Armington agents contain all production activities indexed by a and final demand agents indexed by fd. Subsequently, the final demand agents are separated into households (h), government (gov) and investment (inv). Activities are spilt from commodities, and the former are indexed by a and the latter are indexed by i with some possible alias defined in GAMS. For example, the intermediate demand, $XA_{i,a}$ represents the demand for commodity i by activity a.

In the standard GTAP database, a one-to-one mapping is defined between activities and commodities. The ENVISAGE model is able to work on a non-diagonal make matrix as user-determined of aggregating database. This user-friendly setting is proven useful as we can have different models under different scenarios.

The model has three different production structures, crops (acr), livestock (alv) and others (ax), all subsets of activities (a). Geographically, activities are divided into two zones, rural and urban. Typically, agricultural activities are assigned to the rural zone and all other activities belong to the urban zone. Three key indices power (pb), land (lb) and water (wb) bundles are user-defined and are used to aggregate power supply in the power module, allocate land across sectors in the land supply and allocate water usage in the water supply bundle. Table 2.1 lists out the main indices in the model.

Table 2.1: Sets in ENVISAGE model

Set	Description

$\boldsymbol{aa}$	Armington agents
$\boldsymbol{a}$	Activities (subset of aa)
$\boldsymbol{acr}$	Crop activities (subset of a)
$\boldsymbol{alv}$	Livestock activities (subset of a)
$\boldsymbol{ax}$	All other activities (subset of a)
$\boldsymbol{elya}$	Power activities (subset of a)
$\boldsymbol{fd}$	Final demand (subset of aa)
$\boldsymbol{fdc}$	Final demand excluding household (subset of fd)
$\boldsymbol{h}$	Household (subset of fd)
$\boldsymbol{gov}$	Government account (subset of fd)
$\boldsymbol{inv}$	Investment account (subset of fd)
$\boldsymbol{z}$	Set of zones (elements rur and urb)
$\boldsymbol{i}$	Produced goods
$\boldsymbol{inum}$	Set of manufacturing sectors
$\boldsymbol{fp}$	Factors of production
$\boldsymbol{l}$	Labor categories (subset of fp)
$\boldsymbol{ul}$	Unskilled labor (subset of l)
$\boldsymbol{sl}$	Skilled labor (subset of l)
$\boldsymbol{cap}$	Capital account (subset of fp)
$\boldsymbol{lnd}$	Land account (subset of fp)
$\boldsymbol{nrs}$	Natural resource account (subset of fp)
$\boldsymbol{wat}$	Water account (subset of fp)
$\boldsymbol{k}$	Consumed commodities
$\boldsymbol{nrg}(\boldsymbol{k})$	Energy bundle in consumed commodities
$\boldsymbol{gy}$	Government revenue accounts
$\boldsymbol{itax}$	Indirect taxes (a subset of gy)
$\boldsymbol{ptax}$	Production tax account (a subset of gy)
$\boldsymbol{mtax}$	Import tax account (a subset of gy)
$\boldsymbol{etax}$	Export tax account (a subset of gy)
$\boldsymbol{vtax}$	Tax on factors of production account (a subset of gy)
$\boldsymbol{ctax}$	Carbon tax (a subset of gy)
$\boldsymbol{dtax}$	Direct tax (a subset of gy)
$\boldsymbol{r}$	Regions
$\boldsymbol{s}, \boldsymbol{d}$	Aliases with r (source and destination regions)
$\boldsymbol{rnum}$	Set of regions (subset of r)
$\boldsymbol{rres}$	Residual region (subset of r in single dimension)
$\boldsymbol{em}$	Emission types
$\boldsymbol{pb}$	Power bundle
$\boldsymbol{lb}$	Land bundle
$\boldsymbol{wb}$	Water bundle

A.2 Production Block

Production is implemented using a nested CES (constant elasticity substitution utility function) structure, a standard in many applied general equilibrium models. Three main production structure prototypes, crops, livestock, and all other (the default production structure) are supplemented by two nesting bundles called KEF (the bundle KEF represents the nested combination of capital, skilled labor, energy and the natural resource factors) and energy bundles. This section is a full description of all nests from the top to the bottom. In the end, each of the terminal nodes are the derived demand for the basic components of production – intermediate goods and factors of production.

Each nest is a reproduction for its possible associated vintages. In the comparative static model, there is usually one single vintage. However, there are old vintage as the initial capital installed and new vintage representing the new supply of capital in the dynamic version. The former one designs to be partially flexible across sectors in which the nests are deterministic, while the latter one is fully flexible where the nests depend on the specific design.

Production for each vintage is associated with a unit (marginal) cost of production represented by UC. The post-tax marginal cost of production, PXv (the subscript v represents its associated vintage), is equal to the tax-adjusted pre-tax marginal cost of production in equation ($P1$), where τ^{uc} is the tax on the cost of production and the subscripts r, a, and v represent for region, activity, and vintage. This design allows the user to calculate production activity associated with tax for independent regions and activities.

$$PXv_{r,a,v} = UC_{r,a,v}\left(1 + \tau^{UC}_{r,a,v}\right) \qquad (P1)$$

The aggregate marginal cost of production across vintages, PX, given in equation ($P2$) is the weighted sum of the vintage-specified costs of production with weights given by the production volume shares where XPv and XP represent output by vintage and aggregate output respectively.

$$PX_{r,a}XP_{r,a} = \sum_{v} PXv_{r,a,v}XPv_{r,a,v} \qquad (P2)$$

The output (or market) price, PP, is equal to sum of the marginal cost of production and a markup, π^m*(at this moment always exogenous and set to 0)*, and adjusted by an output tax represented by τ^p in equation ($P3$).

$$PP_{r,a} = (PX_{r,a} + \pi^m_{r,a})\left(1 + \tau^p_{r,a}\right) \qquad (P3)$$

Then, we will focus on the various CES nests representing the production structure by vintage, and the goal of using CES nests is to replicate the substitution and complementarity relations across all of the inputs, so as to show all the intermediate activities.

The top level CES nest represents the combination of output, XPX, with a bundle of non-CO_2 greenhouse gas (GHG) emissions, $XGHG$, which is a typical bundle used to simulate the marginal cost of mitigating non-CO_2 greenhouse gases. When the price of this bundle increases which may be from the tax on emissions, producers substitute away from this relatively high cost inputs. Then equations ($P4$) and ($P5$) representing the derived demands for the output and GHG bundles are introduced respectively, which are the standard CES demand functions where PXP and $PGHG$ represent the prices of the component bundles and UC is the price of the aggregate bundle.

$$XPX_{r,a,v} = \alpha^{XP}_{r,a,v}(A^{XPv}_{r,a,v}\lambda^{XP}_{r,a,v})^{\sigma^{XP}_{r,a,v}-1}\left(\frac{UC_{r,a,v}}{PXP_{r,a,v}}\right)^{\sigma^{XP}_{r,a,v}} XPv_{r,a,v} \qquad (P4)$$

$$XGHG_{r,a,v} = \alpha^{GHG}_{r,a,v}(A^{XPv}_{r,a,v}\lambda^{GHG}_{r,a,v})^{\sigma^{XP}_{r,a,v}-1}\left(\frac{UC_{r,a,v}}{PXGHG_{r,a,v}}\right)^{\sigma^{XP}_{r,a,v}} XPv_{r,a,v} \qquad (P5)$$

To see this, UC, is the marginal cost of production including the price associated with the GHG emissions. There are two standard CES share parameters, α^{XP} and α^{GHG}, and A^{XPv} is a parameter of tech-neutral shift in the production nest and σ^{XP} is the elasticity of substitution between production and the GHG emissions and σ^{GHG} is the elasticity of substitution production and the non-CO_2 greenhouse gases. Also, the production nest considers the input specific technological change representing by the parameters λ^{XP} and λ^{GHG}, typically, those are exogenous. We also define the component price of the CES bundle, UC, which uses the CES dual price formula and could be replaced by the zero-profit condition.

$$UC_{r,a,v} = \frac{1}{A^{XPv}_{r,a,v}}\left[\alpha^{XP}_{r,a,v}\left(\frac{PXP_{r,a,v}}{\lambda^{XP}_{r,a,v}}\right)^{1-\sigma^{XP}_{r,a,v}} + \alpha^{GHG}_{r,a,v}\left(\frac{PXGHG_{r,a,v}}{\lambda^{GHG}_{r,a,v}}\right)^{1-\sigma^{XP}_{r,a,v}}\right]^{\frac{1}{1-\sigma^{XP}_{r,a,v}}} \qquad (P6)$$

Under the scenario of the regional nuclear war, the shock from the global point of view will be introduced to change those two exogenous input technological parameters. Globally, the technology retrogression will cause the drop from the output parameter, λ^{XP}, and the non-CO_2 greenhouse gases, λ^{GHG}, which causes the decrease of the combination output and the increase of the marginal cost of the production.

The second level nest decomposes aggregate production nest of the GHG bundle into two bundles, $ND^1(Intermediate\ demand\ bundle\ excluding\ FERT\ and\ NRG)$ and $VA(value\ added\ \ bundle)$. All intermediate goods except energy bundles and other intermediate goods treated typically in a given activity form the ND^1 bundle. In the default configuration of the model, activity-specific intermediate goods usually contain fertilizers for crop activities and feed for livestock activities. The VA has all factors of production, the energy goods and activity-specific goods those are applicable. Equation $(P7)$ calculates the demands for the top level intermediate demand bundle, ND^1.

$$ND^1_{r,a} = \sum_{v} \alpha^{ND^1}_{r,a,v}\left(\frac{PXP_{r,a,v}}{PND^1_{r,a}}\right)^{\sigma^P_{r,a,v}} XPX_{r,a,v} \qquad (P7)$$

Equation ($P8$) then determines the demand for the VA bundle. Prices for two bundles are PND^1 and PVA respectively, and the substitution elasticity denotes by σ^P.

$$VA_{r,a,v} = \alpha_{r,a,v}^{VA} \left(\frac{PXP_{r,a,v}}{PVA_{r,a,v}}\right)^{\sigma_{r,a,v}^P} XPX_{r,a,v} \qquad (P8)$$

Note that the equation for ND^1 bundle is summed over all vintages. This is because the further decomposition of the ND^1 bundle is independent of the vintage, while the decomposition of the VA bundle is vintage dependent as the substitution elasticities in the bottom nest that are allowed to be different by vintage. In equation ($P9$), the price of XPX is determined as PXP.

$$PXP_{r,a,v} = \left[\alpha_{r,a,v}^{ND^1}\left(PND_{r,a}^1\right)^{1-\sigma_{r,a,v}^P} + \alpha_{r,a,v}^{VA}\left(PVA_{r,a,v}\right)^{1-\sigma_{r,a,v}^P}\right]^{\frac{1}{1-\sigma_{r,a,v}^P}} \qquad (P9)$$

The third level CES nests are reflecting activities to three production structure prototypes of crops (in our model, the crops have disaggregated into 8 specific grain crops), livestock and all other activities. The crop production structure is designed to discover production characterized by shifting between intensification and extensification. Such changes can be made where land is abundant and cheap so that the production can be extended by using more land, and vice versa if the land resource is limited and expensive. Livestock production is characterized by feed against land substitution. The main characteristics of production are the standard capital and labor substitutions in most production structure. Among all three different prototypes, the third level CES will be slightly different.

To capture the difference between structures, two intermediate value added bundles, VA^1 and VA^2 are representing different composition of factors and activity specific intermediate goods. Under the VA bundle, value added bundle without unskilled labor, VA^1 is the top nest. The bottom contains other nests of bundles LAB^{US} (unskilled labor), $Land^d$ (land demand), KEF (value added bundle including capital, skilled labor and NRG) and ND^2 (FERT bundle). LAB^{US}

bundle denotes the demand for the unskilled labor, in the sense of "unskilled", the user may determine the labor categories, for example, the user may have all labor types in this bundle, in which case the skilled labor bundle, LAB^S will be empty. While, the variable $Land^d$ represents the activity's demand for the land factor. The bundle KEF is the nested combination of capital, skilled labor, energy and the natural resource factor. The ND^2 bundle represents the activity – specific demand for intermediates – fertilizers in the case of crops and feed in the case of livestock activities. The table below describes the compositions of these three middle nests for the three production prototypes.

Activity	Bundle composition	Activity	Bundle composition	Activity	Bundle composition
Crops		Livestock		Default	
VA	CES(LAB^{US}, VA^1)	VA	CES(VA^1, VA^2)	VA	CES(LAB^{US}, VA^1)
VA^1	CES(ND^2, VA^2)	VA^1	CES(LAB^{US}, KEF)	VA^1	CES($Land^d$, KEF)
VA^2	CES($Land^d$, KEF)	VA^2	CES($Land^d$, ND^2)		

Equations for the intermediate nests can be written according to the demand for the single component bundles, and the price equations can be descried subsequently. Two bundles VA^1 and VA^2 can be determined by equation ($P10$) and equation ($P11$). VA^1 bundle is a share of VA for all activity, while VA^2 is a share of VA^1 in the case of crops and of VA in the case of livestock. In the default setting of the production structure, there is no require for VA^2 bundle.

$$VA^1_{r,a,v} = \alpha^{VA^1}_{r,a,v} \left(\frac{PVA_{r,a,v}}{PVA^1_{r,a,v}} \right)^{\sigma^{VA}_{r,a,v}} VA_{r,a,v} \qquad (P10)$$

$$VA^2_{r,a,v} = \begin{cases} \alpha^{VA^2}_{r,a,v} \left(\frac{PVA^1_{r,a,v}}{PVA^2_{r,a,v}} \right)^{\sigma^{VA^1}_{r,a,v}} VA^1_{r,a,v} & \text{if } a \in \{Crops\} \\ \alpha^{VA^2}_{r,a,v} \left(\frac{PVA_{r,a,v}}{PVA^2_{r,a,v}} \right)^{\sigma^{VA}_{r,a,v}} VA_{r,a,v} & \text{if } a \in \{Livestock\} \end{cases} \qquad (P11)$$

Equations ($P12$), ($P13$) and ($P14$) determine the bundles LAB^{US}, KEF and ND^2. The subsequent decomposition of these three bundles will be identical for all activities. The LAB^{US} bundle is a share of VA^1 in the case of Livestock and VA in the case of all other activities.

$$LAB^{US}_{r,a} = \begin{cases} \sum_v \alpha^{LAB^{US}}_{r,a,v} \left(\frac{PVA_{r,a,v}}{PLAB^{US}_{r,a}} \right)^{\sigma^{VA}_{r,a,v}} VA_{r,a,v} & \text{if } a \in \{Crop \cup Default\} \\ \sum_v \alpha^{LAB^{US}}_{r,a,v} \left(\frac{PVA^1_{r,a,v}}{PLAB^{US}_{r,a}} \right)^{\sigma^{VA^1}_{r,a,v}} VA^1_{r,a,v} & \text{if } a \in \{Livestock\} \end{cases} \qquad (P12)$$

And KEF bundle is a share of VA^1 in the case of all other activities and VA^2 in the case of Crops.

$$KEF_{r,a,v} = \begin{cases} \alpha^{KEF}_{r,a,v} \left(\frac{PVA^2_{r,a,v}}{PKEF_{r,a,v}} \right)^{\sigma^{VA^2}_{r,a,v}} VA^2_{r,a,v} & \text{if } a \in \{Crops\} \\ \alpha^{KEF}_{r,a,v} \left(\frac{PVA^1_{r,a,v}}{PKEF_{r,a,v}} \right)^{\sigma^{VA^1}_{r,a,v}} VA^1_{r,a,v} & \text{if } a \in \{Default\} \end{cases} \qquad (P13)$$

The ND^2 bundle is a share of VA^1 for Crops and VA^2 for Livestock, which is not used in the default production structure.

$$ND^2_{r,a} = \begin{cases} \sum_v \alpha^{ND^2}_{r,a,v} \left(\frac{PVA^1_{r,a,v}}{PND^2_{r,a}} \right)^{\sigma^{VA^1}_{r,a,v}} VA^1_{r,a,v} & \text{if } a \in \{Crops\} \\ \sum_v \alpha^{ID^F}_{r,a,v} \left(\frac{PVA^2_{r,a,v}}{PND^2_{r,a}} \right)^{\sigma^{VA^2}_{r,a,v}} VA^2_{r,a,v} & \text{if } a \in \{Livestock\} \end{cases} \qquad (P14)$$

The final demand equation determines the demand of the land factor, $Land^d$, which is a share of VA^2 in the case of Crops and Livestock and a share of VA^1 in the case of the default activities. To allow the efficiency improvement, the parameter λ^d is introduced in the use of land. The variable of the price of land is $PLand^p$ that represents the user price of land, which is equal to the market price of land adjusted for an activity – specific tax or subsidy.

$$Land^d_{r,a} = \begin{cases} \sum_v \alpha^{Land^d}_{r,a,v} \left(\frac{\lambda^d_{r,a,v} PVA^2_{r,a,v}}{PLand^p_{r,a}} \right)^{\sigma^{VA^2}_{r,a,v}} \frac{VA^2_{r,a,v}}{\lambda^d_{r,a,v}} & \text{if } a \in \{Crops\} \\ \sum_v \alpha^{Land^d}_{r,a,v} \left(\frac{\lambda^d_{r,a,v} PVA^2_{r,a,v}}{PLand^p_{r,a}} \right)^{\sigma^{VA^2}_{r,a,v}} \frac{VA^2_{r,a,v}}{\lambda^d_{r,a,v}} & \text{if } a \in \{Livestock\} \\ \sum_v \alpha^{Land^d}_{r,a,v} \left(\frac{\lambda^d_{r,a,v} PVA^1_{r,a,v}}{PLand^p_{r,a}} \right)^{\sigma^{VA^1}_{r,a,v}} \frac{VA^1_{r,a,v}}{\lambda^d_{r,a,v}} & \text{if } a \in \{Default\} \end{cases} \qquad (P15)$$

Till this step, the description of the intermediate nests is fully described with the deterministic equations of the intermediate bundles VA, VA^1 and VA^2. In the following equations ($P16$), ($P17$) and ($P18$), they determine the price, PVA, PVA^1 and PVA^2 with respective to three bundles.

$$PVA_{r,a,v} = \begin{cases} [\alpha^{LAB^{US}}_{r,a,v} \left(PLAB^{US}_{r,a} \right)^{1-\sigma^{VA}_{r,a,v}} + \alpha^{VA^1}_{r,a,v} \left(PVA^1_{r,a,v} \right)^{1-\sigma^{VA}_{r,a,v}}]^{\frac{1}{1-\sigma^{VA}_{r,a,v}}} & \text{if } a \in \{Crop \cup Default\} \\ [\alpha^{VA^1}_{r,a,v} \left(PVA^1_{r,a,v} \right)^{1-\sigma^{VA}_{r,a,v}} + \alpha^{VA^2}_{r,a,v} \left(PVA^2_{r,a,v} \right)^{1-\sigma^{VA}_{r,a,v}}]^{\frac{1}{1-\sigma^{VA}_{r,a,v}}} & \text{if } a \in \{Livestock\} \end{cases} \qquad (P16)$$

$$PVA^1_{r,a,v} = \begin{cases} [\alpha^{ND^2}_{r,a,v}\left(PND^2_{r,a}\right)^{1-\sigma^{VA^1}_{r,a,v}} \\ \quad +\alpha^{VA^2}_{r,a,v}\left(PVA^2_{r,a,v}\right)^{1-\sigma^{VA^1}_{r,a,v}}]^{\frac{1}{1-\sigma^{VA^1}_{r,a,v}}} & \text{if } a \in \{Crops\} \\ [\alpha^{LAB^{US}}_{r,a,v}\left(PLAB^{US}_{r,a}\right)^{1-\sigma^{VA^1}_{r,a,v}} \\ \quad +\alpha^{KEF}_{r,a,v}\left(PKEF_{r,a,v}\right)^{1-\sigma^{VA^1}_{r,a,v}}]^{\frac{1}{1-\sigma^{VA^1}_{r,a,v}}} & \text{if } a \in \{Livestock\} \\ [\alpha^{Land^d}_{r,a,v}\left(\frac{PLand^p_{r,a}}{\lambda^d_{r,a,v}}\right)^{1-\sigma^{VA^1}_{r,a,v}} \\ \quad +\alpha^{KEF}_{r,a,v}\left(PKEF_{r,a,v}\right)^{1-\sigma^{VA^1}_{r,a,v}}]^{\frac{1}{1-\sigma^{VA^1}_{r,a,v}}} & \text{if } a \in \{Default\} \end{cases} \qquad (P17)$$

$$PVA^2_{r,a,v} = \begin{cases} [\alpha^{Land^d}_{r,a,v}\left(\frac{PLand^p_{r,a}}{\lambda^d_{r,a,v}}\right)^{1-\sigma^{VA^2}_{r,a,v}} \\ \quad +\alpha^{KEF}_{r,a,v}\left(PKEF_{r,a,v}\right)^{1-\sigma^{VA^2}_{r,a,v}}]^{\frac{1}{1-\sigma^{VA^2}_{r,a,v}}} & \text{if } a \in \{Crops\} \\ [\alpha^{Land^d}_{r,a,v}\left(\frac{PLand^p_{r,a}}{\lambda^d_{r,a,v}}\right)^{1-\sigma^{VA^2}_{r,a,v}} \\ \quad +\alpha^{ND^2}_{r,a,v}\left(PID^F_{r,a}\right)^{1-\sigma^{VA^2}_{r,a,v}}]^{\frac{1}{1-\sigma^{VA^2}_{r,a,v}}} & \text{if } a \in \{Livestock\} \end{cases} \qquad (P18)$$

The subsequent production nests are identical for all three production prototypes. The KEF bundle is the decompositions of two nested bundles, KF bundle representing the composition of capital, skilled labor, water and natural resources, and $XNRG$ bundle representing the energy bundle. In equations ($P29$) and ($P20$), they represent the derived demands for the KF and $XNRG$ bundles, with the bundle prices represented by PKF and $PNRG$ associated with the main substitution elasticity, σ^{KEF}. The CES dual price formula for the price of KEF bundle, $PKEF$, is also presented in equation ($P21$).

$$KF_{r,a,v} = \alpha^{KF}_{r,a,v}\left(\frac{PKEF_{r,a,v}}{PKF_{r,a,v}}\right)^{\sigma^{KEF}_{r,a,v}} KEF_{r,a,v} \qquad (P19)$$

$$XNRG_{r,a,v} = \alpha^{NRG}_{r,a,v}\left(\frac{PKEF_{r,a,v}}{PNRG_{r,a,v}}\right)^{\sigma^{KEF}_{r,a,v}} KEF_{r,a,v} \qquad (P20)$$

$$PKEF_{r,a,v} = \left[\alpha^{KF}_{r,a,v}\left(PKF_{r,a,v}\right)^{1-\sigma^{KEF}_{r,a,v}} + \alpha^{NRG}_{r,a,v}\left(PNRG_{r,a,v}\right)^{1-\sigma^{KEF}_{r,a,v}}\right]^{\frac{1}{1-\sigma^{KEF}_{r,a,v}}} \qquad (P21)$$

Under the KF bundle, it is composed of the KSW bundle, a composition of capital, skilled labor and water and the sector – specific natural resource, $XNRF^d$. The derived demands are represented by the equation ($P22$) and ($P23$) for the KSW bundle and $XNRF^d$ bundle, with the respective prices $PKSW$ and $PNRF^p$. And the main substitution elasticity is denoted σ^{KF}, the natural resource efficiency factor λ^{NRF} is exogenous. The dual price equation for the price of the KF bundle, PKF, is formulated in equation ($P24$).

$$KSW_{r,a,v} = \alpha^{KSW}_{r,a,v}\left(\frac{PKF_{r,a,v}}{PKSW_{r,a,v}}\right)^{\sigma^{KF}_{r,a,v}} KF_{r,a,v} \qquad (P22)$$

$$XNRF^d_{r,a} = \sum_v \alpha^{NRF}_{r,a,v}\left(\frac{\lambda^{NRF}_{r,a,v} PKF_{r,a,v}}{PNRF^p_{r,a}}\right)^{\sigma^{KF}_{r,a,v}} \frac{KF_{r,a,v}}{\lambda^{NRF}_{r,a,v}} \qquad (P23)$$

$$PKF_{r,a,v} = \left[\alpha^{KSW}_{r,a,v}\left(PKSW_{r,a,v}\right)^{1-\sigma^{KF}_{r,a,v}} + \alpha^{NRF}_{r,a,v}\left(\frac{PNRF_{r,a}}{\lambda^{NRF}_{r,a,v}}\right)^{1-\sigma^{KF}_{r,a,v}}\right]^{\frac{1}{1-\sigma^{KF}_{r,a,v}}} \qquad (P24)$$

In the further nesting, the KSW bundle is composed of the KS bundle, a composition of capital and skilled labor, and the water bundle, $XWAT$. Equations ($P25$) and ($P26$) represent the derived demands for the KS bundle and the water bundle, respectively, with the respective prices, PKS and $PWAT$. The main substitution elasticity is denoted σ^{KSW}, and the similar dual price equation for the price of the KSW bundle, $PKSW$, is formulated in equation ($P27$).

$$KS_{r,a,v} = \alpha^{KS}_{r,a,v}\left(\frac{PKSW_{r,a,v}}{PKS_{r,a,v}}\right)^{\sigma^{KSW}_{r,a,v}} KSW_{r,a,v} \qquad (P25)$$

$$XWAT_{r,a} = \sum_v \alpha^{WAT}_{r,a,v}\left(\frac{PKSW_{r,a,v}}{PWAT_{r,a}}\right)^{\sigma^{KSW}_{r,a,v}} KSW_{r,a,v} \qquad (P26)$$

$$PKSW_{r,a,v} = \left[\alpha_{r,a,v}^{KS}\left(PKS_{r,a,v}\right)^{1-\sigma_{r,a,v}^{KSW}} + \alpha_{r,a,v}^{WAT}\left(PWAT_{r,a}\right)^{1-\sigma_{r,a,v}^{KSW}}\right]^{\frac{1}{1-\sigma_{r,a,v}^{KSW}}} \qquad (P27)$$

The KS bundle is then composed of capital demand by vintage, Kv, and the skilled labor bundle LAB^S. The derived demands for capital and the skilled labor bundle with the respective prices PK^p and $PLAB^S$ are represented in equations ($P28$) and ($P29$). The main substitution elasticity is σ^K, and the capital efficiency factor λ^K is also considered exogenous. Equation ($P30$) shows the CES dual price expression for the price of the KS bundle, PKS.

$$K_{r,a,v}^{v} = \alpha_{r,a,v}^{K}\left(\frac{\lambda_{r,a,v}^{K} PKS_{r,a,v}}{PK_{r,a,v}^{p}}\right)^{\sigma_{r,a,v}^{K}} \frac{KS_{r,a,v}}{\lambda_{r,a,v}^{K}} \qquad (P28)$$

$$LAB_{r,a}^{S} = \sum_{v} \alpha_{r,a,v}^{LAB^S}\left(\frac{PKS_{r,a,v}}{PLAB_{r,a}^{S}}\right)^{\sigma_{r,a,v}^{K}} KS_{r,a,v} \qquad (P29)$$

$$PKS_{r,a,v} = \left[\alpha_{r,a,v}^{K}\left(\frac{PK_{r,a,v}^{p}}{\lambda_{r,a,v}^{K}}\right)^{1-\sigma_{r,a,v}^{K}} + \alpha_{r,a,v}^{LAB^S}\left(PLAB_{r,a}^{S}\right)^{1-\sigma_{r,a,v}^{K}}\right]^{\frac{1}{1-\sigma_{r,a,v}^{KS}}} \qquad (P30)$$

The next set of CES nests decomposes the two labor bundles, unskilled labor LAB^{US} and skilled labor LAB^S. Equation ($P31$) provides the decomposition of the bundles where two substitution elasticities are σ^{ul} and σ^{sl}, the producer cost of labor is denoted W^p, and λ^l represents labor efficiency factor. Equation ($P32$) determines the price of the unskilled labor bundle, $PLAB^{US}$, and equation ($P33$) determines the price of the skilled labor bundle, $PLAB^S$. The user decides the composition of the labor bundles by mapping the specific skill types to either the unskilled or skilled labor bundles. All skill levels can be mapped to one of the two bundles, in which case the other bundle would be empty and removed from the model structure. Let $l \in \{Unskilled, Skilled\}$ denote the labor type, then

$$L^d_{r,l,a} = \begin{cases} \alpha^l_{r,l,a}\left(\frac{\lambda^l_{r,l,a} PLAB^{US}_{r,a}}{W^p_{r,l,a}}\right)^{\sigma^{ul}_{r,a}} \frac{LAB^{US}_{r,a}}{\lambda^l_{r,l,a}} & \text{if } l \in \{Unskilled\} \\ \alpha^l_{r,l,a}\left(\frac{\lambda^l_{r,l,a} PLAB^{S}_{r,a}}{W^p_{r,l,a}}\right)^{\sigma^{sl}_{r,a}} \frac{LAB^{S}_{r,a}}{\lambda^l_{r,l,a}} & \text{if } l \in \{Skilled\} \end{cases} \qquad (P31)$$

$$PLAB^{US}_{r,a} = \left[\sum_{ul} \alpha^l_{r,ul,a}\left(\frac{W^p_{r,ul,a}}{\lambda^l_{r,ul,a}}\right)^{1-\sigma^{ul}_{r,a}}\right]^{\frac{1}{1-\sigma^{ul}_{r,a}}} \qquad (P32)$$

$$PLAB^{S}_{r,a} = \left[\sum_{sl} \alpha^l_{r,sl,a}\left(\frac{W^p_{r,sl,a}}{\lambda^l_{r,sl,a}}\right)^{1-\sigma^{sl}_{r,a}}\right]^{\frac{1}{1-\sigma^{sl}_{r,a}}} \qquad (P33)$$

Identically, the next set of CES nests decomposes the three intermediate demand bundles, ND^1, ND^2 and $XWAT$. Note that ND^2 contains activity-specific inputs such as fertilizers in the case of Crops and feed in the case of Livestock. The ND^1 bundle contains all of the other intermediate goods except the water and energy goods. The $XWAT$ bundle contains all designated water commodities from intermediate demand as well as the water factor in some sectors such as irrigated agriculture. Equation $(P34)$ provides the decomposition of the bundles where the key substitution elasticities are σ^{ND^1}, σ^{ND^2} and σ^{WAT}, the producer cost of intermediate goods is given by PA^a, and λ^{IG} represents an efficiency factor for the use of intermediate goods. Equation $(P35)$ determines the price of the ND^1 bundle, PND^1 bundle, and equation $(P36)$ decides the price of the ND^2 bundle, PND^2. The user determines the composition of the intermediate demand bundles by mapping the specific intermediate commodities to one of the two bundles. Let i denote the type of the produced goods.

$$XA_{r,i,a} = \begin{cases} \alpha_{r,i,a}^{IG} \left(\frac{\lambda_{r,i,a}^{IG} PND_{r,a}^{1}}{PA_{r,i,a}^{a}} \right)^{\sigma_{r,a}^{ND^1}} \frac{ND_{r,a}^{1}}{\lambda_{r,i,a}^{IG}} & \text{if } i \in \{ND^1\} \\ \alpha_{r,i,a}^{IG} \left(\frac{\lambda_{r,i,a}^{IG} PND_{r,a}^{2}}{PA_{r,i,a}^{a}} \right)^{\sigma_{r,a}^{ND^2}} \frac{ND_{r,a}^{2}}{\lambda_{r,i,a}^{IG}} & \text{if } i \in \{ND^2\} \\ \alpha_{r,i,a}^{IG} \left(\frac{\lambda_{r,i,a}^{IG} PWAT_{r,a}}{PA_{r,i,a}^{a}} \right)^{\sigma_{r,a}^{WAT}} \frac{XWAT_{r,a}}{\lambda_{r,i,a}^{IG}} & \text{if } i \in \{iw\} \end{cases} \qquad (P34)$$

$$PND_{r,a}^{1} = \left[\sum_{i \in \{ND^1\}} \alpha_{r,i,a}^{IG} \left(\frac{PA_{r,i,a}^{a}}{\lambda_{r,i,a}^{IG}} \right)^{1-\sigma_{r,a}^{ND^1}} \right]^{\frac{1}{1-\sigma_{r,a}^{ND^1}}} \qquad (P35)$$

$$PND_{r,a}^{2} = \left[\sum_{i \in \{ND^2\}} \alpha_{r,i,a}^{IG} \left(\frac{PA_{r,i,a}^{a}}{\lambda_{r,i,a}^{IG}} \right)^{1-\sigma_{r,a}^{ND^2}} \right]^{\frac{1}{1-\sigma_{r,a}^{ND^2}}} \qquad (P36)$$

Then, equation ($P37$) decides the demand for the water factor. At this moment, only irrigated crops have any water demand. And the equation ($P38$) determines the price of the $XWAT$ bundle where the subset iw is the span of the set of water commodities.

$$H2O_{r,a}^{d} = \alpha_{r,a}^{H2O} \left(\frac{\lambda_{r,a}^{H2O} PWAT_{r,a}}{PH2O_{r,a}^{p}} \right)^{\sigma_{r,a}^{WAT}} \frac{XWAT_{r,a}}{\lambda_{r,a}^{H2O}} \qquad (P37)$$

$$PWAT_{r,a} = \left[\sum_{i \in \{iw\}} \alpha_{r,i,a}^{IG} \left(\frac{PA_{r,i,a}^{a}}{\lambda_{r,i,a}^{IG}} \right)^{1-\sigma_{r,a}^{WAT}} + \alpha_{r,a}^{H2O} \left(\frac{PH2O_{r,a}^{p}}{\lambda_{r,a}^{H2O}} \right)^{1-\sigma_{r,a}^{WAT}} \right]^{\frac{1}{1-\sigma_{r,a}^{WAT}}} \qquad (P38)$$

The final set of nests in production concern the energy bundle, $XNRG$. It will be decomposed into demand for the energy commodities The energy bundle is first decomposed into electric and non-electric bundles. The latter is then decomposed into a coal bundle and a non-coal bundle. The oil and gas bundle is then split into a gas bundle and an oil bundle. The four remaining bundles, electric, coal, oil and gas represent a combination of existing or future energy sources. The electric bundle would hold the 'ely' commodity, the coal bundle would hold the 'coa'

commodity, the oil bundle would hold the 'oil' and 'p_c' commodities and the gas bundle would hold the 'gas' and 'gdt' commodities. Non-GTAP commodities would be mapped to one of the existing bundles such that 'p_c' could be split into gasoline and diesel, or could include ethanol or bio-diesel.

Thus, equation ($P39$) determines the demand for the electric bundle, XA^{ely}. Equation ($P40$) determines the demand for the non-electric bundle, $XNELY$. Both equations have the substitution elasticity denoted σ^{ELY}. Then, the aggregate price of energy, $PNRG$ is descried in equation ($P41$).

$$XA_{r,a,v}^{ELY} = \alpha_{r,a,v}^{ELY} \left(\frac{PNRG_{r,a,v}}{PA_{r,a,v}^{ELY}} \right)^{\sigma_{r,a,v}^{ELY}} XNRG_{r,a,v} \qquad (P39)$$

$$XNELY_{r,a,v} = \alpha_{r,a,v}^{NELY} \left(\frac{PNRG_{r,a,v}}{PNELY_{r,a,v}} \right)^{\sigma_{r,a,v}^{ELY}} XNRG_{r,a,v} \qquad (P40)$$

$$PNRG_{r,a,v} = \left[\alpha_{r,a,v}^{ELY} \left(PA_{r,a,v}^{ELY} \right)^{1-\sigma_{r,a,v}^{ELY}} + \alpha_{r,a,v}^{NELY} \left(PNELY_{r,a,v} \right)^{1-\sigma_{r,a,v}^{ELY}} \right]^{\frac{1}{1-\sigma_{r,a,v}^{ELY}}} \qquad (P41)$$

Equation ($P42$) determines the demand for the coal bundle, XA^{coa}. Equation ($P43$) determines the demand for the oil and gas bundle, $XOLG$. Both equations have the substitution elasticity denoted σ^{NELY}. Then, equation ($P44$) describes the aggregate price of the non-electric bundle, $PNELY$.

$$XA_{r,a,v}^{COA} = \alpha_{r,a,v}^{COA} \left(\frac{PNELY_{r,a,v}}{PA_{r,a,v}^{COA}} \right)^{\sigma_{r,a,v}^{NELY}} XNELY_{r,a,v} \qquad (P42)$$

$$XOLG_{r,a,v} = \alpha_{r,a,v}^{OLG} \left(\frac{PNELY_{r,a,v}}{POLG_{r,a,v}} \right)^{\sigma_{r,a,v}^{NELY}} XNELY_{r,a,v} \qquad (P43)$$

$$PNELY_{r,a,v} = \left[\alpha_{r,a,v}^{COA} \left(PA_{r,a,v}^{COA} \right)^{1-\sigma_{r,a,v}^{NELY}} + \alpha_{r,a,v}^{OLG} \left(POLG_{r,a,v} \right)^{1-\sigma_{r,a,v}^{NELY}} \right]^{\frac{1}{1-\sigma_{r,a,v}^{NELY}}} \qquad (P44)$$

The remaining two energy bundles are oil and gas and emanate from the $XOLG$ bundle. Equation ($P45$) determines the demand for the oil bundle, XA^{OIL} . Equation ($P46$) determines the demand for the gas bundle, XA^{GAS} . Both equations share the substitution elasticity σ^{OLG}. Equation ($P47$) then describes the aggregate price of the oil and gas bundle, $POLG$.

$$XA_{r,a,v}^{OIL} = \alpha_{r,a,v}^{OIL} \left(\frac{POLG_{r,a,v}}{PA_{r,a,v}^{OIL}} \right)^{\sigma_{r,a,v}^{OLG}} XOLG_{r,a,v} \qquad (P45)$$

$$XA_{r,a,v}^{GAS} = \alpha_{r,a,v}^{GAS} \left(\frac{POLG_{r,a,v}}{PA_{r,a,v}^{GAS}} \right)^{\sigma_{r,a,v}^{OLG}} XOLG_{r,a,v} \qquad (P46)$$

$$POLG_{r,a,v} = \left[\alpha_{r,a,v}^{OIL} \left(PA_{r,a,v}^{OIL} \right)^{1-\sigma_{r,a,v}^{OLG}} + \alpha_{r,a,v}^{GAS} \left(PA_{r,a,v}^{GAS} \right)^{1-\sigma_{r,a,v}^{OLG}} \right]^{\frac{1}{1-\sigma_{r,a,v}^{OLG}}} \qquad (P47)$$

The final nest in the energy bundle is to decompose the four aggregate energy bundles into their constituent parts that represent the Armington demand for the energy commodities. Equation ($P48$) reflects the Armington demand for energy commodity e, XA, where the cost to producers is given by PA^{a}. The key substitution elasticity for each energy bundle is given by σ^{NRG}. Equation ($P49$) represents the price of the aggregate energy bundles, PA^{NRG}. Let e denote the demand type of the energy of energy bundle.

$$XA_{r,e,v} = \sum_{v} \alpha_{r,e,a,v}^{EIO} \left(\frac{\lambda_{r,e,a,v}^{e} PA_{r,a,v}^{NRG}}{PA_{r,e,a}^{a}} \right)^{\sigma_{r,a,v}^{NRG}} \frac{XA_{r,a,v}^{NRG}}{\lambda_{r,e,a,v}^{e}} \quad \text{if } e \in \{NRG\} \qquad (P48)$$

$$PA_{r,a,v}^{NRG} = \left[\sum_{e \in \{NRG\}} \alpha_{r,e,a,v}^{EIO} \left(\frac{PA_{r,e,a}^{a}}{\lambda_{r,e,a,v}^{e}} \right)^{1-\sigma_{r,a,v}^{NRG}} \right]^{\frac{1}{1-\sigma_{r,a,v}^{NRG}}} \qquad (P49)$$

In this paper, the comparison will be used on the baseline check after the disaggregation of the "$GrainCrops$" from the original. The shock will then be considered globally as the shift of the technology parameters, which will be represented in the yield drop from three mean corps,

“$Rice$”, “$Wheat$” and “$Soybean$”. Those simulations are from the climate model under the scenario from 2020 to 2050. For more than 200 countries including regions, the yield will be generated from the climate model in each year, so there are total 31 shocks from each country including region.

A.3 Commodity Supply

In this model, each activity a is allowed to produce one or more commodities. For instance, the rubber industry could produce both regular rubber products such as auto parts and the natural rubber derivatives include liquid natural rubber and deproteinized rubber. Similarly, a single commodity can be produced by one or more activities. For example, the electricity commodity can be produced by several generation activities such as thermal, nuclear, hydro, and renewables. The joint production can be captured by a constant elasticity of transformation (CET) function with some perfect transformations, while the aggregation of output from multiple activities is captured with a constant elasticity of substitution (CES) preference function with commodity homogeneity where the law-of-one-price holds.

For the power activities, aggregation to the single electricity commodity uses a nested CES structure, which will be distinguished from non-electric goods.

A.3.1 Non-electric Goods

This section explains the make matrix for all non-electric commodities, thus all equations describe all commodities indexed by i except for the electricity commodity. In equation ($S1$), the allocation of output, $XP_{r,a}$ from activity a is to supply commodity i. The variable X represents the supply of the commodity i by activity a, the transformation elasticity is also provided by ω^s.

The model can be applied in perfect transformation in different markets, in which case the law-of-one-price holds to avoid the arbitrage.

$$\begin{cases} X_{r,a,i} = \gamma^{p}_{r,a,i} \left(\frac{P_{r,a,i}}{PP_{r,a}} \right)^{\omega^{s}_{r,a}} XP_{r,a} & \text{if } \omega^{s}_{r,a} \neq \infty \\ P_{r,a,i} = PP_{r,a} & \text{if } \omega^{s}_{r,a} = \infty \end{cases} \qquad (S1)$$

Equation ($S2$) is an equilibrium condition determining the aggregate output of activity a, AP, and in the case of perfect transformation, it is an aggregation of the individual supplies.

$$PP_{r,a}XP_{r,a} = \sum_{i} P_{r,a,i}X_{r,a,i} \qquad (S2)$$

The supply of commodity i is the (CES) aggregation of output of one or more activities a. Equation ($S3$) determines the demand for output a to compose commodity i, X**.** Note that equation ($S1$) determines supply while equation ($S3$) determines demand. The substitution elasticity is given by σ^{S} and the standard CES share parameter is defined by α^{S}. The model allows for perfect substitution where the law-of-one-price holds. And the market price is determined by i, PS, in ($S4$). Equations ($S1$) and ($S3$) describe supply and demand respectively.

$$\begin{cases} X_{r,a,i} = \alpha^{s}_{r,a,i} \left(\frac{PS_{r,i}}{P_{r,a,i}} \right)^{\sigma^{s}_{r,i}} XS_{r,i} & \text{if } \sigma^{s}_{r,i} \neq \infty \\ P_{r,a,i} = PS_{r,i} & \text{if } \sigma^{s}_{r,i} = \infty \end{cases} \qquad (S3)$$

$$PS_{r,i}XS_{r,i} = \sum_{a} P_{r,a,i}X_{r,a,i} \qquad (S4)$$

A.3.2 Domestic Electricity Supply

The electricity bundle uses a nested CES bundle structure instead of a single nest as the following figure. The top nest contains all power supply with distribution and transmission services to form aggregate domestic electric supply. The power nest combines several different power bundles. Subsequently, each power bundles are formed by the different power activities embedded into the different power bundles, which is user friendly under different scenarios. If the power bundles are composed of coal-based, oil-based and gas-based generations, nuclear, hydro, and others. Under the power database of GTAP, base and peak coal load will be mapped into the coal power bundle so as the oil, gas, nuclear, and all other power activities including wind, solar, and hydro could all be mapped into the corresponding power bundles. For the future advanced technology strategy, the technological generation of each nature resource will be mapped into the corresponding power bundle. (graph insert)

In equation ($S5$), the demand for electricity services indexed by activities etd as intermediates used to produce one or more electric commodities indexed by ely, which is linked to the total supply of power, XS^{pow}. Typically, there is a single transmission and distribution activity and a single electricity commodity. The normal specification assumes a Leontief technology such as a substitution elasticity of zero. Equation ($S6$) then determines the demand for the power bundle, and it is a bundle containing all generation, but excludes the transmission and distribution services.

$$X_{r,etd,ely} = \alpha^{s}_{r,etd,ely} \left(\frac{PS_{r,ely}}{P_{r,etd,ely}} \right)^{\sigma^{el}_{r,ely}} XS_{r,ely} \qquad \text{(S5)}$$

$$XPOW_{r,ely} = \alpha^{pow}_{r,ely} \left(\frac{PS_{r,ely}}{PPOW_{r,ely}} \right)^{\sigma^{el}_{r,ely}} XS_{r,ely} \qquad \text{(S6)}$$

The supply price of aggregate electricity is determined in equation ($S7$).

$$PS_{r,ely} = \left[\alpha^{s}_{r,etd,ely} \left(P_{r,etd,ely} \right)^{1-\sigma^{el}_{r,ely}} + \alpha^{pow}_{r,ely} \left(PPOW_{r,ely} \right)^{1-\sigma^{el}_{r,ely}} \right]^{\frac{1}{1-\sigma^{el}_{r,ely}}} \qquad \text{(S7)}$$

Next, we decompose aggregate demand for power into a user-determined number of power bundles, indexed by pb. Then, equation ($S8$) gives the demand for the power bundles. Note the aggregate price used is $PPOWN$ instead of $PPOW$, the latter one is the average price of the power bundle and the former one is the price index defined in equation ($S9$).

$$XPB_{r,pb,ely} = \alpha_{r,pb,ely}^{pb} \left(\frac{PPOWN_{r,ely}}{PPB_{r,pb,ely}}\right)^{\sigma_{r,ely}^{pow}} XPOW_{r,ely} \qquad \text{(S8)}$$

$$PPOWN_{r,ely} = \left[\sum_{pb} \alpha_{r,pb,ely}^{pb} \left(PPB_{r,pb,ely}\right)^{-\sigma_{r,ely}^{pow}}\right]^{-\frac{1}{\sigma_{r,ely}^{pow}}} \qquad \text{(S9)}$$

In the standard CES, the two prices are identical. The power decomposition uses the adjusted CES, which preserves the additivity property of the CES components. The demand expressions in both versions of the CES are similar. But, the expression for the aggregate price index differs and the price is not equal to the average price calculated using the zero profit condition. As we see in equation ($S10$), it evaluates the average price, $PPOW$.

$$PPOW_{r,ely} XPOW_{r,ely} = \sum_{pb} PPB_{r,pb,ely} XPB_{r,pb,ely} \qquad \text{(S10)}$$

The subsequent nest decomposes various power bundles into component power activities. Each power activity is mapped to one of the aggregate power bundles. Equation ($S11$) determines the demand of power generated from activity $elya$ which is mapped to power bundle pb.

$$X_{r,elya,ely} = \alpha_{r,elya,ely}^{s} \left(\frac{PPBN_{r,pb,ely}}{P_{r,elya,ely}}\right)^{\sigma_{r,pb,ely}^{pb}} XPB_{r,pb,ely} \quad \text{if } elya \in pb \qquad \text{(S11)}$$

While in equations ($S12$) and ($S13$), they define the price index for the power bundle pb as derived from the adjusted CES price index expression, and the average price of the power bundle pb using the zero profit condition.

$$PPBN_{r,pb,ely} = \left[\sum_{elya \in pb} \alpha^{s}_{r,elya,ely}\left(P_{r,elya,ely}\right)^{-\sigma^{pb}_{r,pb,ely}}\right]^{-\frac{1}{\sigma^{pb}_{r,pb,ely}}} \quad \text{(S12)}$$

$$PPB_{r,pb,ely} XPB_{r,pb,ely} = \sum_{elya \in pb} P_{r,alya,ely} X_{r,elya,ely} \quad \text{(S13)}$$

A.4 Income Block

Final agents contain three domestic in the model including households (h), an aggregate government sector (gov), and an aggregate investment sector (inv). Factor income, net taxes, accrues to the private household, government revenues are generated from both indirect and direct taxes in the economy, and investment income is the sum of domestic and foreign savings. Part of capital income flows to a global holder of equity, which portions out profits from the global fund. However, remittances are incorporated and are completely bilateral.

The depreciation calculates as the replacement cost of the estimated deprecation in equation ($I1$). The parameter δ^{f} is used to differ from the physical rate of depreciation, although it is usually identical. PFD_{inv} is the unit cost of investment and K^{s} is the non-normalized level of the aggregate capital stock. The normalized level of the capital stock is scaled to the initial aggregate remuneration of capital, while the non-normalized level is needed for calculating the depreciation allowance and in the dynamic equation for updating the aggregate capital stock.

$$DeprY_{r} = \delta^{f}_{r} PFD_{r,inv} K^{s}_{r} \quad (I1)$$

The model merges some level of income flow from labor and income. Certain percentage of each region's profit flows to a global equity fund that disburses its aggregate income across regions. Equation ($I2$) shows the flow of a region's profits net of taxes, $YQTF$, to the global equity fund.

$$YQTF_r = \chi_r^f\left(1-\kappa_r^f\right)\left(\sum_a\left[\sum_v PK_{r,a,v}K_{r,a,v}^v + \pi_{r,a}^m XP_{r,a}\right] - DeprY_r\right) \quad (I2)$$

Total income for the global equity fund, $TrustY$, is provided by equation ($I3$). Foreign profit inflows, $YQHT$, are represented by equation ($I4$). Remittances from country r to country s for labor of skill l is determined by Equation ($I5$), and it is calculated net of taxes on wages.

$$TrustY = \sum_r YQTF_r \quad (I3)$$

$$YQHT_r = \chi_r^f TrustY \quad (I4)$$

$$Remit_{s,l,r} = \chi_{s,l,r}^r\left(1-\kappa_{r,l}^l\right)\sum_a W_{r,l,a}L_{r,l,a}^d \quad (I5)$$

Equation ($I6$) describes household income, YH. It is the sum across all activities of factor income, at market prices and net of taxes and depreciation.

$$\begin{aligned} YH_r = {} & \sum_l\left(1-\kappa_{r,l}^l\right)\sum_a W_{r,l,a}L_{r,l,a}^d + (1-\kappa_r^k)\left(\sum_a\left[\sum_v PK_{r,a,v}K_{r,a,v}^v + \pi_{r,a}^m XP_{r,a}\right] - DeprY_r\right) \\ & + (1-\kappa_r^t)\sum_a PLand_{r,a}Land_{r,a}^d + (1-\kappa_r^n)\sum_a PNRF_{r,a}XNRF_{r,a}^d \\ & + (1-\kappa_r^\omega)\sum_a PH2O_{r,a}H2O_{r,a}^d + YQHT_r - YQTF_r + \sum_d\sum_l Remit_{r,l,d} \\ & - \sum_s\sum_l Remit_{s,l,r} \quad (I6) \end{aligned}$$

Household income also includes net foreign capital income and net remittances. Factor returns at the price producers pay have a superscript p, which is absent from the factor returns at market prices. Equation ($I7$) describes disposable income, YD, where κ^h is the marginal (and average) rate of tax on household income. Macro closure is discussed below.

$$YD_r = (1 - \kappa_r^l)YH_r \quad (I7)$$

The following equations describe government revenues, contained in the variable $YGOV$ of an additional index for different revenue streams (gy). Equation ($I8$) describes revenues from production and cost taxes. The production tax is applied on the producer price including of the markup. The index ptx is denoted revenue, so equation ($I9$) describes revenues generated on the factors of production including labor, capital, land and natural resources. The revenue index is given by vtx. Equation ($I10$) determines revenues generated by consumption of goods, essentially a sales tax, and the sum is over all domestic agents indexed by aa, and the relevant price is the market price of good i. The equation combines the two different Armington options. In the first case, the sourcing of goods is made at the national aggregated level so that all users have a common Armington price denoted PAT, which will be adjusted by the end-user tax. And the second option assumes a top level Armington sourcing by agent in which case the domestic sales tax is differentiated by source. The revenue index is given by itx, so equation ($I11$) describes revenues generated by import tariffs which are summed over all source countries s, where the first regional index is the exporting region and the second regional index is the importing destination region. The tariffs are applied to the border price of imports, PWM. The revenue is given by mtx, so equation ($I12$) describes revenues generated by export taxes and subsides, which are summed over all destination countries (d). They are applied to the producer price of exports, PE. The revenue index is given by etx. Equation ($I13$) describes revenues generated from carbon taxes, which holds for either Armington specification. The revenue index is given by ctx. Direct taxes are described in equation ($I14$), where the revenue index is given by dtx. Direct taxes are imposed on specific factor incomes and there is a net direct tax on total household income after factor taxes that balances the government account.

$$YQTF_{r,ptx} = \sum_a \left[\tau^p_{r,a}\left(PK_{r,a} + \pi^m_{r,a}\right)XP_{r,a} + \sum_v \tau^{uc}_{r,a} UC_{r,a,v} XPv_{r,a,v} \right] \quad (I8)$$

$$YGOV_{r,vtx} = \sum_a \left[\sum_l \tau^l_{r,l,a} W_{r,l,a} L^d_{r,l,a} + \sum_v \tau^k_{r,a,v} PK_{r,a,v} K^v_{r,a,v} \right]$$

$$+ \sum_a \left[\tau^l_{r,a} PLand_{r,a} Land^d_{r,a} + \tau^n_{r,a} PNRF_{r,a} XNRF^d_{r,a} \right]$$

$$+ \sum_a \left[\tau^w_{r,a} PH2O_{r,a} H2O^d_{r,a} \right] \quad (I8)$$

$$YGOV_{r,vtx} = \begin{cases} \sum_{aa} \sum_i \tau^a_{r,i,aa} \gamma^{eda}_{r,i,aa} PAT_{r,i} XA_{r,i,aa} & \text{if } ArmFlag = 0 \\ \sum_{aa} \sum_i \tau^d_{r,i,aa} \gamma^{edd}_{r,i,aa} PDT_{r,i} XD_{r,i,aa} & \\ +\tau^d_{r,i,aa} \gamma^{edd}_{r,i,aa} PDT_{r,i} XD_{r,i,aa} & \text{if } ArmFlag \neq 0 \end{cases} \quad (I10)$$

$$YQTF_{r,mtx} = \sum_s \sum_i \tau^m_{s,i,r} PWM_{s,i,r} XW^d_{s,i,r} \quad (I11)$$

$$YQOV_{r,etx} = \sum_d \sum_i \tau^e_{r,i,d} PE_{r,i,d} XW^s_{r,i,d} \quad (I12)$$

$$YGOV_{r,ctx} = \begin{cases} \sum_{em} \sum_i \sum_{aa} \chi^{Emi}_{em} \rho^{Emi}_{r,em,i,aa} \emptyset^{Emi}_{r,em,i,aa} \tau^{Emi}_{r,em,aa} XA_{r,i,aa} & \text{if } ArmFlag = 0 \\ \sum_{em} \sum_i \sum_{aa} \chi^{Emi}_{em} \rho^{Emi,d}_{r,em,i,aa} \emptyset^{Emi}_{r,em,i,aa} \tau^{Emi}_{r,em,aa} XD_{r,i,aa} & \\ +\chi^{Emi}_{em} \rho^{Emi,m}_{r,em,i,aa} \emptyset^{Emi}_{r,em,i,aa} \tau^{Emi}_{r,em,aa} XM_{r,i,aa} & \text{if } ArmFlag \neq 0 \end{cases} \quad (I10)$$

$$YGOV_{r,dtx} = \sum_l \kappa^l_{r,l} \sum_a W_{r,l,a} L^d_{r,l,a} + \kappa^k_r \left(\sum_a \left[\sum_v PK_{r,a,v} K^v_{r,a,v} + \pi^m_{r,a} XP_{r,a} \right] - DeprY_r \right)$$

$$+ \kappa^t_r \sum_a PLand_{r,a} Land^d_{r,a} + \kappa^n_r \sum_a PNRF_{r,a} XNRF^d_{r,a} + \kappa^\omega_r \sum_a PH2O_{r,a} H2O^d_{r,a}$$

$$+ \kappa^h_r YH_r \quad (I14)$$

Equation ($I15$) describes the financing of gross investment. The variable YFD represents final demand expenditures. In terms of value, it is indexed by fd taking values of h, gov and inv respectively for households, government and investment. Gross investment is equivalent to the sum of all savings from domestic from households (S^h), government (S^g), foreign (S^f) evaluated using a global price index, PW^{sav}, and the depreciation allowance in equation ($I1$). Macro closure defines what variable this equation determines. In the default closure, investment is saving driven and therefore this equation determines the nominal level of investment. If investment is fixed, then this equation could determine either household or public savings.

$$YFD_{r,inv} = S_r^h + S_r^g + PW^{sav} S_r^f + DeprY_r \quad (I15)$$

References

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