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A Static Computable General Equilibrium Model of World Energy and Agricultural Markets

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A Static Computable General Equilibrium Model of World Energy and Agricultural Markets

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1 Introduction

This document provides a description of a preliminary version of a static comparative, multi-region, computable general equilibrium (CGE) trade model, based on Global Trade Analysis Project (GTAP) data. Model structure is similar to that of McDonald et al. (2005) and McDonald et al. (2006), but with more detailed representations of agricultural and biofuels-related activities.

This model facilitates analysis of the general equilibrium effects of biofuels policy. Partial equilibrium methods are certainly helpful for analyzing the effects of marginal increases in biofuels production on agricultural markets and trade. However such methods are less appropriate for considering other very interesting questions, such as the effects of very large changes from the status quo, the likely effects of new technologies for which no historical data exist, and the increasing influence of biofuels production on fossil energy market equilibria. Computable general equilibrium methods can overcome these limitations.

Several aspects of the current biofuel market and policy environment motivate the development of this type of tool. The Energy Independence and Security Act of 2007 established ambitious new Renewable Fuel Standards (RFSs), which mandate annual use of 15 billion gallons of grain ethanol by 2015, and 21 billion gallons of "advanced biofuel" (most likely cellulosic ethanol) by 2022. Essentially no cellulosic ethanol is currently being produced, and the advanced RFS in particular represents a substantial change from the status quo. Moreover, the production of 36 billion gallons of renewable fuel by 2022 will certainly exert a substantial influence on fossil energy markets. The long-run economic effects of these policy and market developments on agricultural markets, land use, and U.S. energy independence are poorly characterized at this time, and analysis of these issues using appropriate methods is sorely needed. Policymakers will doubtlessly consider numerous changes in biofuel and other energy policy in coming years, necessitating analyses using the type of model presented here.

After describing the data used, we provide a fairly non-technical description of the current version of the model. The unique biofuels-related components of the model are described in relatively greater detail than other more typical CGE model components.

2 Data

The GTAP database is the primary data source used for calibrating the model (Gehlhar et al., 1997). Version six of the database is employed. The database contains information on the flow of funds within and between 87 regions of the world. Individual database entries are total payments during the year 2001 from one database entity to another, where entities include the regions themselves, households, production sectors, governments, factor markets, commodity markets, and capital markets.

Within each region, 57 production activities and corresponding final commodities are represented (at least potentially). These production sectors make payments to five primary factors of production: natural resources, land, capital, skilled labor, and unskilled labor. Payments to the factors ultimately are passed to a single representative household within each region. A single government entity receives payments reflecting a variety of taxes, and makes transfer payments to households. Payments for final commodities are made by the governments, by households, by production sectors, and capital investment accounts. With the exception of payments for trade and transport services, the counter-parties for all inter-regional payments are recorded, facilitating rich modeling of trade flows.

The GTAP database is structured in an input-output format, with separate matrices for each region representing final demands for domestically produced commodities, tax payments, industry payments for primary factors of production, inter-regional payments, etc. The GTAP data is converted to social accounting matrix (SAM) format using the method of McDonald and Thierfelder (2004). In this format all data concerning each individual region are represented in a single matrix that reflects a common intra-regional price basis. The SAM is square, with each account being represented by both a row and column of the matrix. Individual entries in the SAM reflect total payments from the account represented by the entry's column to the account represented by the entry's row. Various aggregations of the full database are typically used for this model, wherein like payments to and from individual entities of the same type (primary factors, production sectors, or regions) are summed to reduce the computational burden of solving the model.

3 Model Overview

The behavior of production sectors and households is described using a constant returns to scale (CRTS), nested constant elasticity of substitution (CES) production technology. The model code accommodates the Leontief and Cobb-Douglas limiting cases of the CES function, so that any value for the elasticity of substitution can be used as appropriate for different types of market entities, and different instances of those entities. The nested CES functions are calibrated against the base year data from the SAM, which details each entity's receipts and payments made to all inputs. Prices of inputs recorded in the SAM are assumed to be unity in the base year, implicitly defining the units in which the commodities and factors are measured. Values for all elasticities of substitution are specified exogenously, and the values of the other CES parameters are then calculated as functions of that elasticity, the *ad valorem* tax rates, input prices, and payments to inputs, as described in Shoven and Whalley (1992). This process is recursive over the nest hierarchies, with lower nests being calibrated first before higher nests. Model solutions are based on CES demand functions using the specified elasticities of substitution and other calibrated parameters.

Model equations other than those describing behavior provide system constraints, which preserve accounting identities and impose model closure rules.

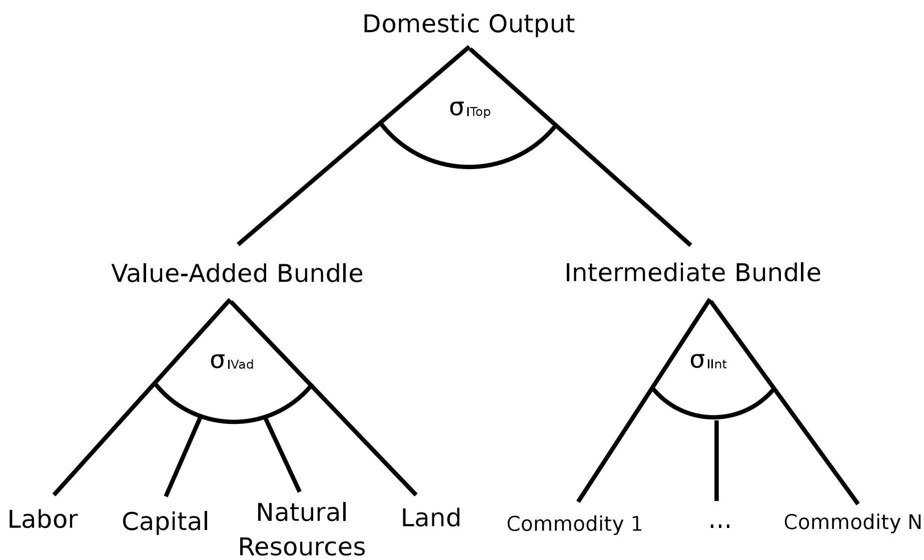

Figure 1: Standard Commodity Production Technology

The heart of the model is a set of inequalities describing a Walrasian market equilibrium. Inequalities describe factor and domestic commodity market balance within each region, and analogous inequalities describe trade balance among regions.

The balance of this section describes model components, in non-mathematical terms, organized by types of economic activities and actors. Biofuels-related model components are described in somewhat greater detail, as these components diverge from typical CGE model construction.

3.1 Factor Markets and Production Sectors

The primary factors of production, labor, capital, land, and natural resources, are assumed to be immobile across regions. Factors are fully mobile across production sectors, and the equilibria generated by the model are therefore long-run. Within each region, a single representative household sells its full endowment of all primary factors to production sectors. The factors are assumed homogeneous, and a single market-clearing price for each factor determines its allocation within each region.

Each commodity production sector maximizes profits. In the top nest of the production function, each sector employs a composite value-added good and a composite intermediate good. The composite value-added good is produced using the four primary factors, while the the composite intermediate good is produced using the output of other sectors.[1] Inputs into the two lower nests are

[1] Technically, the intermediate goods themselves are composites of domestic output and

subject to *ad valorem* taxes on their use. Production activities in each sector are subject to a zero-profit condition, whereby the payments made for all inputs, inclusive of use taxes, must equal the payments received for output for a positive level of output.

3.2 Biofuels-related Sectors

Numerous model enhancements relate to biofuels production. The GTAP database does not contain information on biofuels production, and data from other sources, including USDA reports, and agronomic and engineering studies are used to calibrate and incorporate production sectors related to biofuels. New production sectors relate to feedstock production and production of biofuels themselves. Additionally, the existing petroleum and coal products sector is modified to reflect the incorporation of biofuels into the energy products distribution stream. Each of these enhancements is now described in turn.

A switchgrass production sector is added to the model, as switchgrass is a leading candidate cellulosic ethanol feedstock. Switchgrass is a summer perennial grass that is native to North America and is a dominant species of the remnant tall grass prairies in the United States. Switchgrass is resistant to many pests and plant diseases and has the potential to produce high yields with low fertilizer application rates. Switchgrass can be grown on marginal land with fairly moderate inputs and can also protect the soil from erosion problems (Duffy and Nanhou, 2002). The two main types of switchgrass are upland types (grows to 5 or 6 feet tall) and lowland types (grows to 12 feet tall). Switchgrass planting and harvesting is very similar to other hay crops and the same machinery can be used for harvesting. When switchgrass is produced for biomass, it can be cut once or twice a year. Switchgrass is currently grown as a forage crop on limited acreage in the Conservation Reserve Program (CRP), and on various test plots throughout the United States.

Adding a dedicated switchgrass sector follows the approach taken by McDonald et al. (2006), and contrasts with the approach of Raneses et al. (1998) who considered switchgrass an output of an existing "other hay" sector. As in McFarland et al. (2004), we calibrate the production technology for this sector using cost share and total cost information. Following McDonald et al. (2006), cost shares for the inputs into switchgrass production are set to levels similar to those of similar crops in the GTAP database. Switchgrass is produced using the standard technology depicted in Figure 1. The cost of switchgrass production in the base year is based on a broad literature review (Duffy, 2008; Duffy and Nanhou, 2002; Khanna and Chapman, 2001; Mapemba et al., 2007; Perrin et al., 2003, 2008; Turhollow, 2000; Vogel, 2007; Walsh et al., 2003; Ugarte et al., 2003). Individual estimates from these sources were adjusted based on their varying assumptions, and a average price of approximately $63 per ton is used in calibrating this sector. This cost is exclusive of transportation costs, which are borne by the consumer. In contrast to standard practice in CGE

imported goods, as described in subsection 3.6.

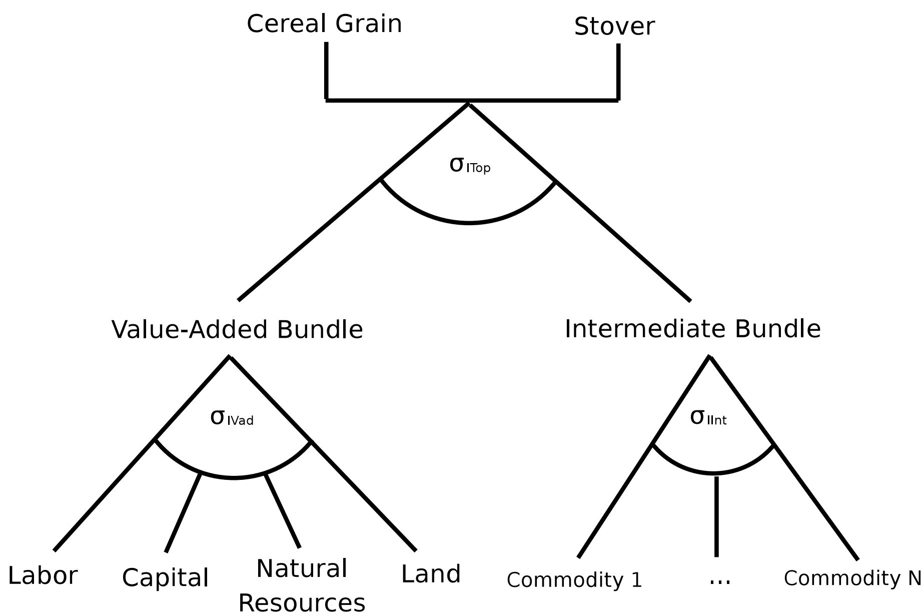

Figure 2: Joint Production of Coarse Grains and Stover

model calibration, we use actual price per ton for switchgrass, and model quantities are therefore measured in standard physical units (c.f., physical units that are implied by a base year price of unity).

Corn stover is a byproduct of corn grain production and consists of the stalk, leaf, husk, and cob remaining in the field after the corn grain harvest. The main component of corn stover is cellulose. Corn stover composition and moisture content varies due to several factors such as region, soil type, weather, corn variety, and harvesting methods (Aden et al., 2002). Half of the corn crop yield by weight is corn stover, but it is generally left in the field after harvest. A portion of the stover can be collected and used as a biomass source for cellulosic ethanol production, but a certain percentage must be left on the ground to avoid soil erosion. Less than 5% of corn stover production is generally used presently (Hettenhaus and Wooley, 2000).

Given that large quantities of corn stover are currently produced, yet little is utilized, they are likely the lowest cost biomass source as cellulosic ethanol production begins (Gallagher et al., 2003). Consideration of corn stover is therefore critical to ensuring that an unrealistic level of dedicated energy crop production is not provoked by increases in cellulosic ethanol production. We incorporate stover as a fixed proportions joint product of cereal grain production (Figure 2). Costs for producing corn stover are therefore not separately modeled, but are instead shared with the cereal grains production activity. Collection and transportation costs for stover in this model are borne by the consumer.

A portion of the corn stover can be collected and used as a biomass source for cellulosic ethanol production. The amount that can be removed varies by region, soil conditions, and harvest activities. Corn stover is very important in preserving the organic matter and nutrients in the soil following corn grain harvesting and preventing soil erosion. It is difficult to establish a corn stover removal rate that is ideal for all regions due to variations in soil and weather conditions. Additionally, stover collection is restricted by several constraints relating to available collection technologies. For the purposes of this model, we assume a stover collection rate of 30%, which is consistent with available collection technology and is believed sustainable from an erosion standpoint.

Three ethanol production sectors are incorporated into the model, reflecting three possible feedstocks: cereal grain, switchgrass, and corn stover. Fuel ethanol production from grain feedstocks is a mature technology, and numerous estimates of production costs and their structures are available. The grain ethanol sector employs the standard nested CES structure depicted in Figure 1. Calibration of the production function is again accomplished by calibrating cost shares and total cost to available cost studies, as described above for switchgrass production. Numerous such studies were reviewed (Tiffany et al., 2008; Environmental Protection Agency, 2007; Eidman, 2007; Burnes et al., 2005; Shapouri and Gallagher, 2005; Wallace et al., 2005; Tiffany and Eidman, 2003; McAloon et al., 2000), and the individual unit cost estimates were adjusted to reflect a 2001 corn price (corresponding to our base year). The average adjusted unit cost estimate of about $1.08 is employed in calibration. Cost shares for individual inputs were averaged over available studies as well, and those averages were used for calibration.

So-called cellulosic ethanol is widely viewed as a promising avenue for development of sustainable, domestically produced liquid fuel. Cellulosic ethanol is produced by converting cellulose from plants into sugars which can then be fermented and distilled using standard technology. Enzymatic hydrolysis is the technology being most actively pursued for cellulosic conversion, and this is the technology against which we calibrate cellulosic ethanol production sectors. This technology is much less mature than that for grain-based ethanol, and production on large commercial scales has yet to commence. Cost estimates therefore reflect a fair amount of uncertainty. Available cost studies vary widely in their assumptions, particularly regarding production scale, feedstock costs, and enzyme costs.

We incorporate both corn stover and switchgrass-based ethanol production sectors in the model. All available cost estimates concern producing cellulosic ethanol from switchgrass (Aden et al., 2002; McAloon et al., 2000; Wallace et al., 2005; Wooley et al., 1999), and these cost data are used for calibrating both cellulosic ethanol production sectors. The different cost estimates are normalized to reflect identical biomass costs, and to reflect the cost of biomass collection and transportation. The standard production technology (Figure 1) is employed for both sectors. The resulting average normalized estimate of total unit cost of $2.08 is used in the calibration. Individual costs from the studies reviewed were categorized and aggregated as appropriate, and the these categorized costs were mapped to the primary factors and commodities employed in the model. As with the biomass and grain ethanol production sectors, actual unit costs are used as the base year price rather than unity, and the corresponding quantity variables are therefore measured in standard physical units.

All biofuels are consumed by a petroleum and coal products production sector. This arrangement is similar to Reilly and Paltsev (2007), who assume that the output of their "bio-oil" sector is a perfect substitute for refined oil products. The arrangement is also somewhat similar to McDonald et al. (2006), who consider switchgrass as a substitute for crude oil in the production of refined petroleum products. More generally, the use of biofuels as an input into production of petroleum products is consistent with the nature of actual biofuel marketing, which typically involves the distribution of blends of biofuels and traditional petroleum-based fuels.

The petroleum and coal products production sector is depicted in Figure 3. Traditional petroleum and coal products are produced in a sub-tree structured like all other commodity production functions in the model. Ethanols produced using grain, switchgrass and stover are used to produce a composite ethanol good. A high degree of substitutability among ethanol varieties is assumed. Finally, the composite ethanol good and the composite traditional coal and petroleum-based products good are used in the production of the new, more broadly defined petroleum and coal products commodity. The top nest is calibrated using the value of production of the traditional coal and petroleum products, the value of production of fuel ethanol in 2001, and the 2001 grain ethanol cost of production of about \$1.08. A moderately high degree of substitution is specified for this top nest.

3.3 Households

A single representative household is specified for each region. The household is endowed with the four primary factors of production, which are sold to production sectors. The government imposes *ad valorem* taxes on factor incomes. Household income is also augmented by transfer payments from the government. The household is subject to a budget constraint, by which net income is exactly exhausted by utility production.

Utility production by each region's representative household is illustrated in Figure 4. The household saves a portion of income and consumes a composite consumer good, which is produced in a lower nest using the individual final goods represented in the model. Such consumption is, of course, subject to sales taxes.

3.4 Government

Each region features a government which collects several types of taxes. All taxes are specified *ad valorem*, with default rates inferred from the base year SAM. Taxes on factor incomes are levied against the representative household, and taxes on factor use are levied against production sectors. Taxes are levied on

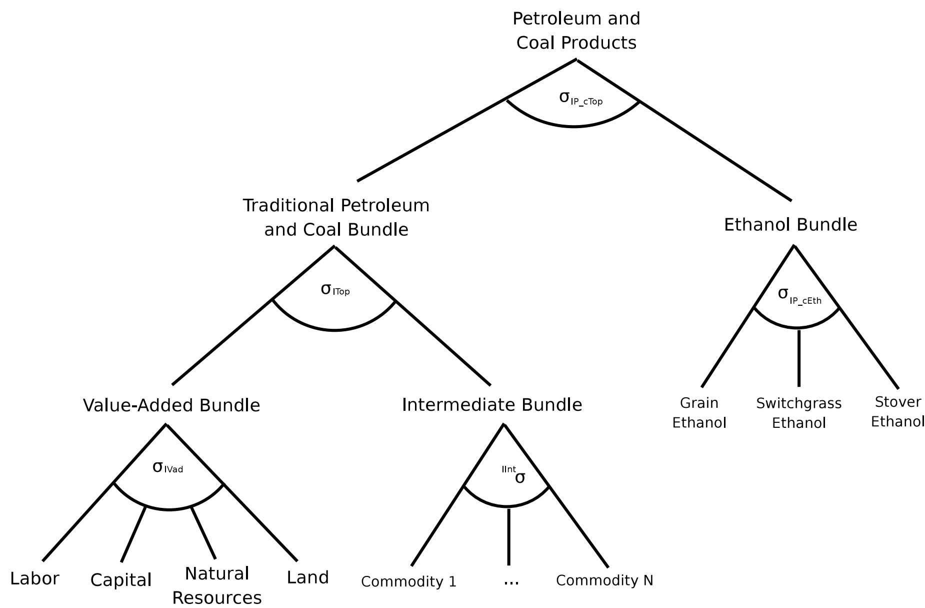

Figure 3: Petroleum and Coal Products Sector

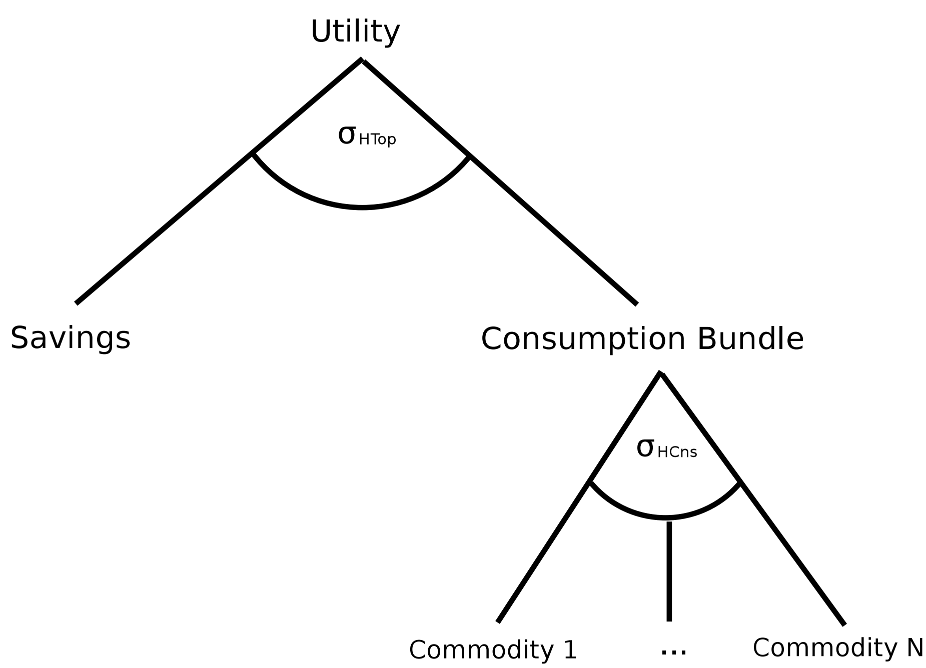

Figure 4: Household Utility Production

imports and exports of commodities. A tax is levied on commodity production, and sales taxes are levied on purchases of commodities for final consumption, intermediate use in production, or investment use. Perhaps surprisingly, a tax on government consumption of commodities is specified in the model, as this is needed to accommodate the GTAP data for some regions.

Government budget balance is imposed for each region. All government income is exactly exhausted, and is distributed in fixed proportions via transfer payments to the representative household and purchases of final goods.

3.5 Trade

Each region potentially trades final commodities with other regions. Demand for commodities reflects the Armington convention, whereby domestically produced and imported goods are imperfect substitutes (Armington, 1969). For each imported commodity in each region, imports from foreign regions are used to produce a composite import good (Figure 5). The domestic production of the commodity that is allocated for domestic consumption and the corresponding composite import good are then used to produce a composite final commodity that allocated among end users.

Domestic consumption is allocated between domestic use and export to foreign regions using nested constant elasticity of transformation (CET) functions (also depicted in Figure 5). Production is initially allocated between domestic use and export, and then the export commodity is allocated among individual destinations. Both imports and exports are potentially subject to tariffs, rates for which can be partner region-specific.

Goods are valued within each region in their local currencies, net of all tariffs and inclusive of transport margins in the case of imports, for purposes of determining import and export behavior. Corresponding F.O.B. values in a global reference currency are calculated for purposes of international trade.

A single trade and transport commodity is consumed in the import process, based on commodity, source, and destination-specific transport margins. The trade and transport commodity is assumed perfectly homogeneous, and is imported by all regions from a "globe" region. The globe region imports the transport good from all exporting regions, and internally determines a global price that equilibrates global supply and demand. This assumption of a homogeneous transport good with a single global price is necessary because the GTAP database does not reveal the specific destination regions for exports of trade and transport services. All such exports must consequently be pooled together, valued and distributed by an artificial global transport services aggregator.

3.6 Commodity Markets

Within each region, the final composite consumption commodities are allocated to end use by households, intermediate use in production, government consumption, and investment use. All forms of commodity use are potentially subject to taxation. Model solutions feature a market-clearing price that equilibrates

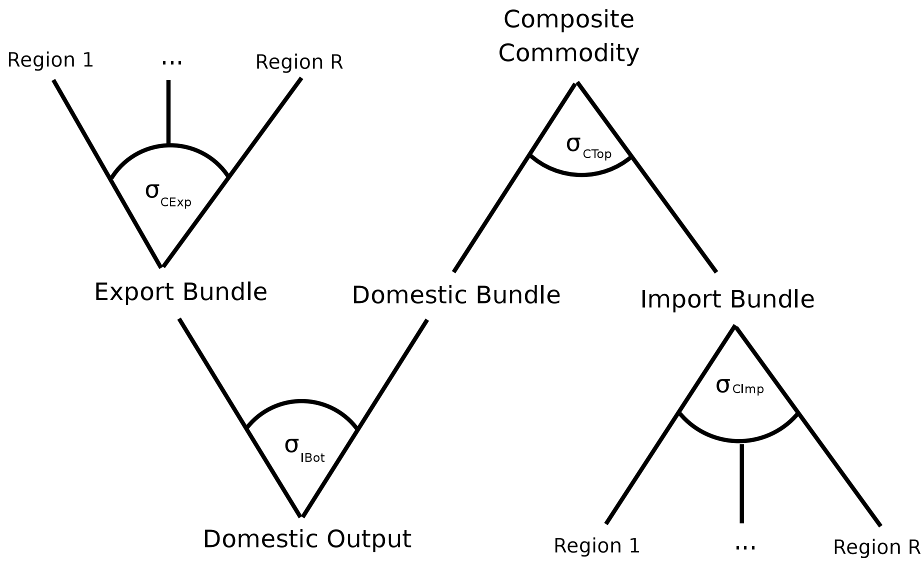

Figure 5: Commodity Trade System

aggregate demand across all uses to the supply determined by a region-wide representative importer and aggregator of the domestic good and composite imported commodity, as described in the previous sub-section.

3.7 Model Closure

Primary factors are fully employed in each region. Government tax rates and government savings are fixed. Government spending is flexible, adjusting to just exhaust (variable) government revenue within each region. Exchange rates are flexible (with the exception of a reference region), and net foreign capital outflows from each region are fixed in terms of the world reference currency. Each region's representative household has a fixed marginal propensity to save, and investment purchases adjust to reflect changes in savings.

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