AgriLIFE RESEARCH & EXTENSION
Texas A&M System

TEXAS A&M UNIVERSITY

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

AFPC Research Paper 11-1

September 2011

AFPC

Agricultural and Food Policy Center

Department of Agricultural Economics
Texas AgriLife Research
Texas AgriLife Extension Service
Texas A&M University

College Station, Texas 77843-2124
Telephone: (979) 845-5913
Fax: (979) 845-3140
http://www.afpc.tamu.edu

A static computable general equilibrium model of World Energy and Agricultural Markets (WEAM)

Henry L. Bryant
Texas A&M University

Jody L. Campiche
Oklahoma State University

Jiamin Lu
Texas A&M University

September 7, 2011

Contents

1 Introduction

This document provides a description 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 land use and agricultural and biofuels-related activities.

This model facilitates analysis of the general equilibrium effects of biofuels policy. Partial equilibrium methods are useful 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 36 billion gallons of biofuels by 2022, of which 21 billion gallons are required to be "advanced biofuels". Moreover, a portion of the advanced mandate must be satisfied by "cellulosic biofuels". Essentially no cellulosic biofuels are 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 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 description of the CGE model. The unique biofuels-related components of the model are described in relatively greater detail than other more typical CGE model components. Section 4 describes the calibration of key elasticities of substitution and transformation. Section 5 describes the calibration of the model's biofuel-related sectors. Section 6 describes an additional, second-stage model component, in which changes in equilibria calculated in the CGE are used to determine changes in global food insecurity.

2 Data

The GTAP database is the primary data source used for calibrating the model (Gehlhar et al., 1997). Version seven of the database is employed. The database contains information on the flow of funds within and between 113 regions of the world. Individual database entries are total payments during the year 2004

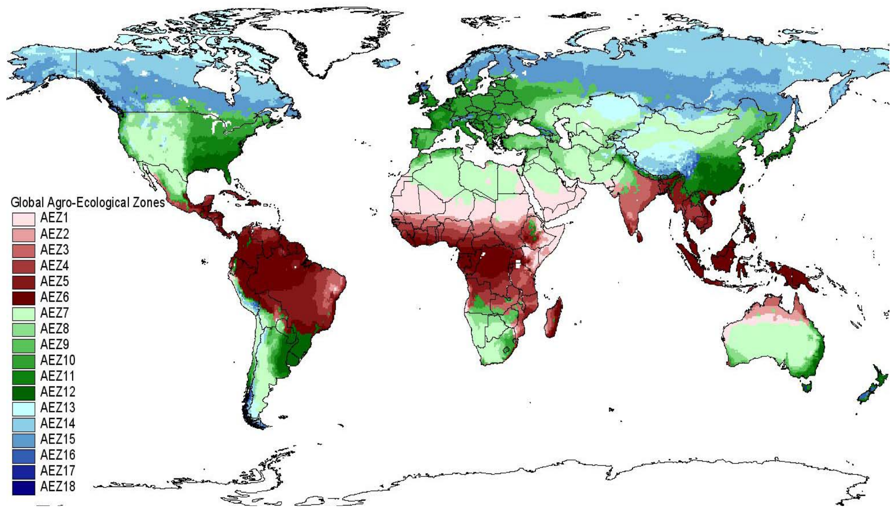

Figure 1: Global Endowments of Land in Agro-ecological Zones (AEZs; source: Monfreda et al., 2009)

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 primary factors of production: natural resources, capital, skilled labor, unskilled labor, and land of various types. 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.

A supplementary GTAP database on land use is employed, as described in Lee et al. (2009). This supplementary database records payments by production sectors within each region to land in each of 18 separate agro-ecological zones (AEZs). These are areas that are relatively homogeneous with respect to moisture, length of the annual growing period, and climate (Koppen-style climate classification). There are six categories of moisture and growing period (arid with 0-59 growing days, dry semi-arid with 60-119 growing days, etc.), and three climate classifications (tropical, temperate, and boreal), for a total of 18 AEZs. Global endowments of land in the AEZs are illustrated in Figure 1.

The GTAP database is structured in an input-output format, with separate

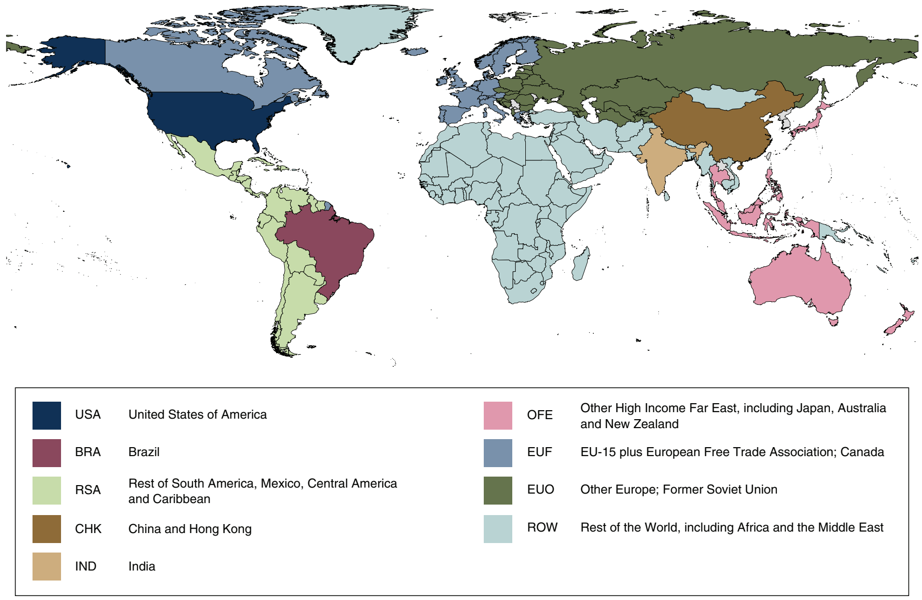

Figure 2: Model Regions

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 payments to and from some individual entities of the same type (primary factors, production activities, or regions) are summed to reduce the computational burden of solving the model. The default regional aggregation employs nine world regions, as illustrated in Figure 2. The default aggregation of production activities employs the full detail of the GTAP data over agricultural and energy-related activites, but aggregates over other activities such as services, manufacturing, etc. Thirty-five activities are derived from the GTAP database, and additional seven biofuels-related activities are incorporated, as listed in Table 1.

Table 1: Production Activities

Activities from GTAP data:		*Biofuels activities:*
pdr	Paddy rice	US switchgrass
wht	Wheat	US grain ethanol
gro	Other cereal grains	US cellulosic ethanol
v_f	Fruits and vegetables	US vegetable oil biodiesel
osd	Oil seeds	US algal biodiesel
c_b	Sugar cane and beets	Brazilian sugarcane ethanol
pfb	Plant-based fibers	Chinese grain ethanol
ocr	Other crops	
ctl	Livestock (cattle, sheep, goats)	
oap	Other animals and products	
rmk	Raw milk	
wol	Wool and silk worm cocoons	
frs	Forestry and logging	
fsh	Fishing	
coa	Coal mining	
oil	Crude oil extraction	
gas	Natural gas extraction	
omn	Other mineral mining	
cmt	Meat prodcuts (corresponds to ctl)	
omt	Other meat products	
vol	Vegetable oils and fats	
mil	Dairy products	
pcr	Processed rice	
sgr	Processed sugar	
ofb	Other food and beverage products	
clt	Textiles and clothing products	
wdp	Wood and paper products	
p_c	Petroleum and coal products	
crp	Chemical rubber and plastic products	
mfg	Other manufactured products	
ely	Electricity	
gdt	Gas manufacturing and distribution	
wtr	Water	
srv	Services	
trn	Transportation	

3 Model Description

The behavior of production activities and households is described using constant returns to scale, 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 commodity and factor quantities 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 before higher nests. Model equilibria solutions are characterized by mixed complementarity relationships among first-order conditions and solution constraints 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. The heart of the model is a set of excess supply functions describing a Walrasian market equilibrium. These inequalities describe factor and domestic commodity market balance within each region, and analogous inequalities describe trade balance among regions. These inequalities, along with corresponding market prices, are used to characterize system equilibrium as set of mixed complementarity relationships.

The balance of this section describes model components organized by types of economic activities and actors. Biofuels-related and land use model components are described in somewhat greater detail, as these components diverge from typical CGE model specification and are of critical importance in applications of this model.

3.1 Factor Markets and Production Activities

The primary factors of production, labor, capital, natural resources, and land, are assumed to be immobile across regions. Factors are fully mobile across production activities, 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 (with the exception of land as described below), and a single market-clearing price for each factor determines its allocation within each region.

Each production activity maximizes profits. In the top nest of the production function, each activity employs a composite value-added-energy input, a composite intermediate input, and a composite land input (for land-using activities).

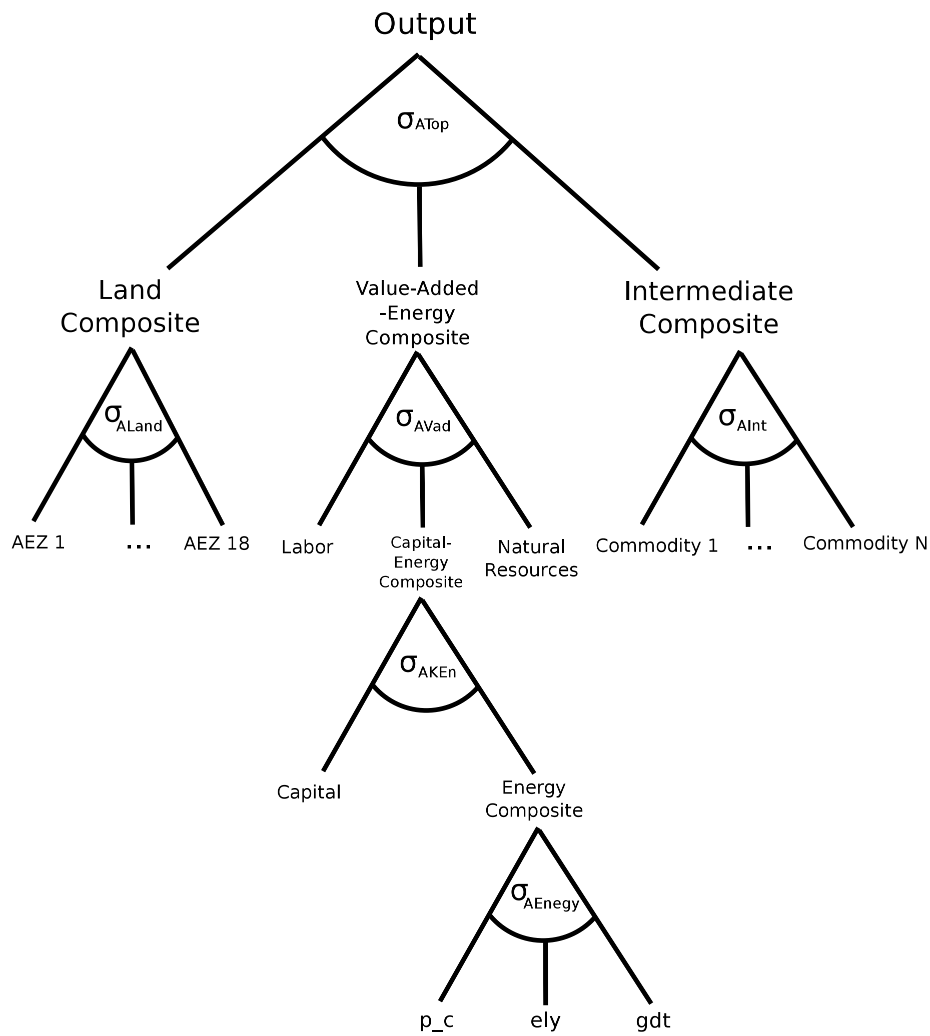

Figure 3: Standard Commodity Production Technology

The value-added-energy input is produced in a nest that takes labor, natural resources, and a capital-energy composite as inputs. The capital-energy composite is produced using a capital and energy composite good. This arrangement is illustrated in Figure 3. The separation of land at the top level is motivated by the need to treat substitution between land and other inputs very carefully for agricultural activities. The nesting arrangement among value-added and energy inputs is motivated by empirical evidence suggesting minimal substitution between capital and energy, but much greater substitution possibilities between labor and either of capital or energy. This evidence is described in Section 4. The composite intermediate good is produced using finished commodities other than energy commodities.[1] The composite land input is produced using land from (potentially) all of the 18 AEZs within each region.

Inputs into the lower nests are subject to *ad valorem* taxes on their use. Production activities 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, when the output level is non-zero.

3.2 Land Transformation

We employ a land transformation scheme similar to that of the GTAP-BIO model (Hertel et al., 2010). Each region has endowments of land for each of the 18 AEZs. Land owners supply this endowment to forestry and agriculture according to a constant elasticity of transformation (CET) revenue function. This allows land rents to differ for these alternative uses, and facilitates frictional transformation of land use as relative returns vary. In a second stage CET nest, agricultural land is allocated between cropland and pastureland. This is illustrated in Figure 4.

Land of each of these final transformed types (forestry, crop, pasture) is implicitly assumed homogeneous. The dairy and livestock-related production activities in each region (ctl, rmk, wol) compete for land in markets for pastureland for each AEZ. The other, primary agricultural production activities compete for land in markets for cropland for each AEZ in each region. Production activities ultimately use land from each AEZ to produce a composite land input using CES technology, as illustrated in Figure 3. This reflects imperfect substitution among land from different AEZs in production of particular commodities.

3.3 U.S. Biofuels-related Activities

Interesting model features relate to U.S. 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.

[1]Technically, commodities entering into domestic consumption are themselves composites of domestic output and imported goods, as described in subsection 3.7.

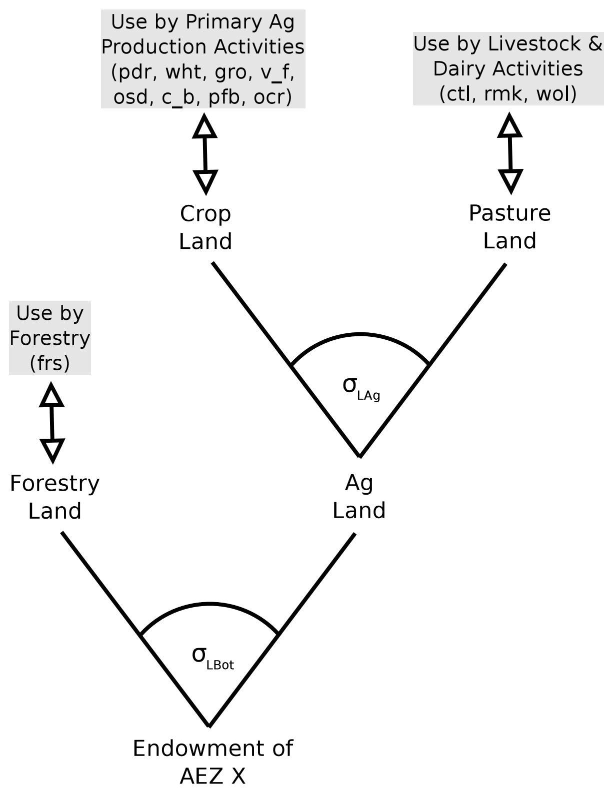

Figure 4: Land Transformation

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. Calibration of the switchgrass production sector is described in Section 5.1.

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 currently (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 5). 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

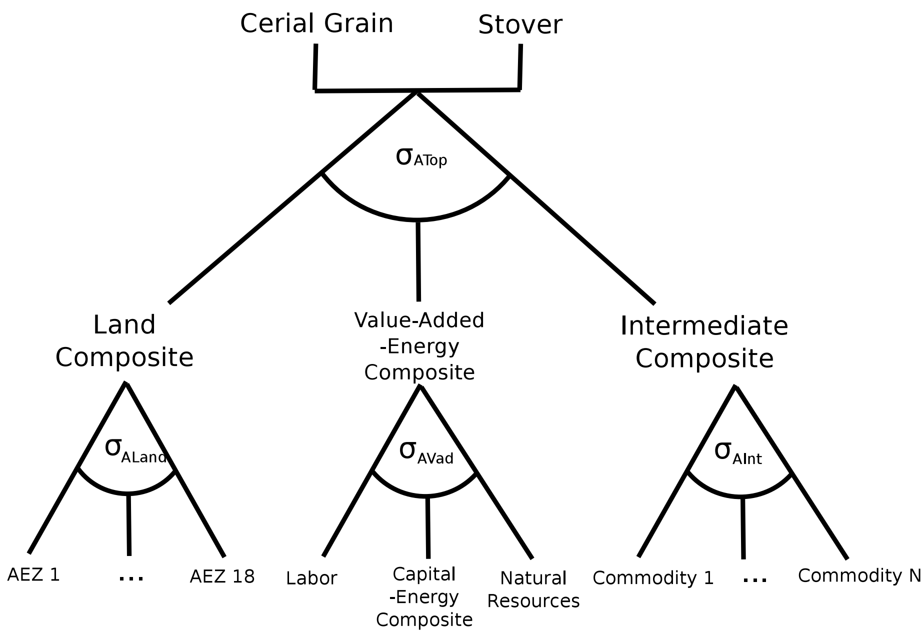

Figure 5: Joint Production of Coarse Grains and Stover

collection technology and is believed sustainable from an erosion standpoint.

Two U.S. ethanol production sectors are incorporated into the model, reflecting two possible feedstocks: cereal grains and biomass. Fuel ethanol production from grain feedstocks is a mature technology, and numerous estimates of production costs and their structure are available. Calibration of the grain ethanol production sector is described in Section 5.1.

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 of 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 as biomass feedstocks for cellulosic ethanol production. Calibration of the cellulosic ethanol production sector is also described in Section 5.1.

Two biodiesel production activities are incorporated into the model. A fatty acid methyl ester (FAME) biodiesel activity produces fuel via transesterification using vegetable oil as a feedstock. This is the traditional and predominant form of biodiesel production worldwide. As an established technology currently operating at commercial scales, we are confident in the cost estimates used in calibrating this activity. Calibration of this activity is described in Section 5.2.

An algal activity reflects both feedstock (algal oil) production and conversion to fuel. Substantial challenges to and uncertainty regarding real-world implementation of this activity exist, as described in Wijffels and Barbosa (2010) and Lundquist et al. (2010). In this activity, microalgae is produced using one of two possible technologies: open ponds or photobioreactors. In the former, algae is grown in water in open, outdoor raceways that are injected with carbon dioxide and continuously stirred. Various parameters for pond configuration (e.g., water depth and square footage), pond seeding (continuous vs. batch), harvesting (continuous, semi-continuous, or batch, using various methods such as centrifuging, flocculation, or electrocoagulation), nutrient addition, and population "crash" handling are currently under investigation. The open pond approach to algae production attempts to minimize capital costs at the expense of less control over growing conditions. The photobioreactor technology, by contrast, accepts higher capital costs in a effort to create ideal conditions for algae growth. Photobioreactors are closed systems consisting of transparent growth containers in which the light intensity, nutrient availability, and temperature can be carefully controlled.

Following production and harvesting of algae, oil and other constituents are separated in an extraction process. As with algae growth and harvesting, substantial uncertainty currently exists as to the technically and economically optimal extraction process, and various possibilities are under investigation. After extraction, algae oil is used in our model activity to produce a biodiesel fuel using a transesterification process. Our representation of this activity also accommodates the possibility of joint production of both algae meal and high-value oils. Characteristics and potential value of the meal are described in Gogichaishvili (2011). In general, current research into algal fuel production suggests quite high production costs relative to other biofuels, and this activity is therefore incorporated as a latent technology that becomes active only under suitable policy scenarios. Calibration of our algae activity is described in Section 5.2.

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 6. Traditional petroleum and coal products are produced in a nested sub-tree structured like all other commodity production functions in the model. Biofuels and the composite traditional coal and petroleum-based products good are used in the production of the new, more broadly defined

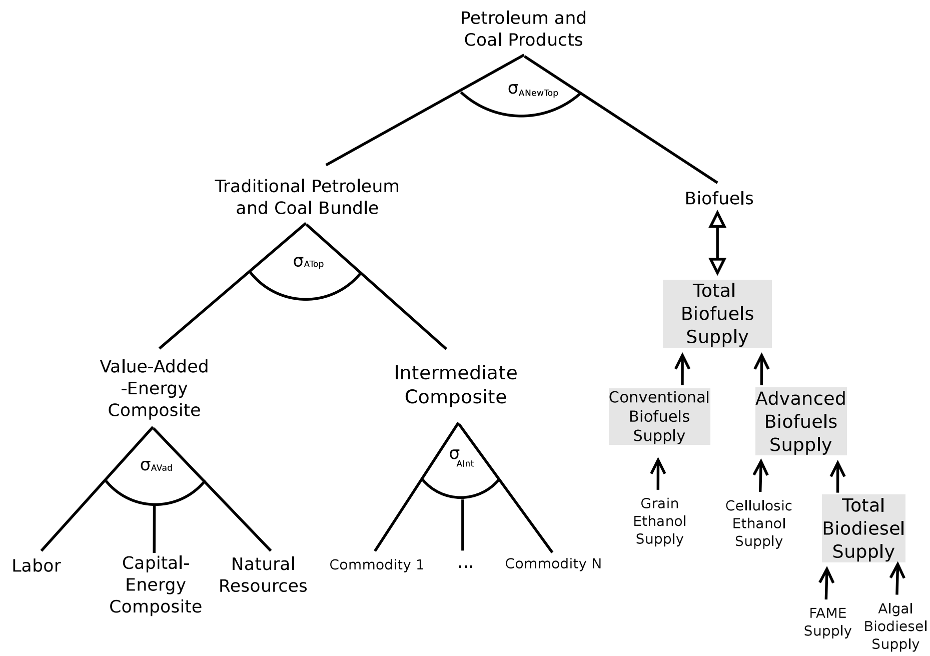

Figure 6: Petroleum and Coal Products Sector

petroleum and coal products commodity. The top nest is calibrated using the value of production of the traditional coal and petroleum products, the quantity of fuel ethanol produced in 2004, and the 2004 grain ethanol cost of production of about \$1.21. Note that cellulosic ethanol and algal biodiesel production are not used in the calibration of this nest as these fuels were neither produced nor consumed in 2004. Advanced biofuels are instead incorporated as a latent technologies that become active under appropriate market or policy conditions.

Production of U.S. biofuels is aggregated in various ways to reflect the structure of the revised Renewable Fuel Standards set forth in the Energy Independence and Security Act of 2007 (RFS2). These aggregations are also depicted in Figure 6. Under RFS2, production mandates are nested. There is a total biofuels mandate (36 billion gallons of ethanol-equivalent by 2022), which must be satisfied using a minimum quantity of "advanced" biofuels (21 billion gallons by 2022). Under RFS2 rules, our grain ethanol production activity represents a "conventional" biofuel, while the cellulosic ethanol and both biodiesel sectors represent advanced biofuels (EPA, 2010a,b). Furthermore, the mandated quantity of advanced biofuels must be comprised of minimum quantities of biodiesel (at least 1 billion gallons of ethanol-equivalent by 2012 and beyond) and cellulosic biofuels (16 billion gallons by 2022).

Quantities of ethanol are modeled in gallons (not abstract units such that base year prices equal unity), so imposition of production mandates is straightforward. Under RFS2 rules, biodiesel mandates are described in ethanol-equivalent volumes. We calibrate our biodiesel activities using these units as well (i.e., quantities are measured in 84,000 BTU units rather than gallons of biodiesel). Again, this facilitates straightforward imposition of RFS2 mandates as they are commonly described.

Currently in the model, ethanol is produced using either grain or biomass. The resulting ethanol is assumed to be homogeneous for purposes of use, and in the absence of a binding use mandate the two varieties should command the same price. Analogously, biodiesel produced by our two different production activities is assumed homogeneous in use and price in the absence of binding use mandates.

In the presence of binding use mandates, various biofuels must be allowed to command different prices. This is accomplished by requiring the petroleum and coal products activity to purchase aggregate biofuel output at a quantity-weighted price, and allowing the various advanced biofuels to collect price premiums above the grain ethanol price if use mandate are binding. This scheme is described by several equations and complementarity relationships in the model. The average cost of aggregate U.S. biofuels consumed is given by

$$P_{ave} = \left(\frac{1}{\sum_j Q_j} \right) \sum_i \left(P_i - V_i \right) Q_i, \tag{1}$$

for $i, j \in \{GEth, CEth, FAME, Algal\}$, where the $GEth$ denotes grain-based ethanol, $CEth$ corresponds to cellulosic ethanol, and so forth. P_i and Q_i represent prices and ethanol-equivalent quantities of fuel i, respectively, and V_i represents a volumetric government incentive for use. Default values for V_i are comprised of the volumetric ethanol excise tax credit (VEETC) of \$0.45 per gallon for grain ethanol, and VEETC plus additional incentives totaling \$1.00 per gallon for cellulosic ethanol. For biodiesel, V_i represents the \$1.01 per gallon Biodiesel Tax Credit (adjusted to reflect our 84,000 BTU units rather than gallons).

The prices of the advanced biofuels relative to that of grain ethanol are

$$P_{CEth} = P_{GEth} + \lambda_{adv} + \lambda_{CEth} \tag{2}$$

$$P_{FAME} = P_{GEth} + \lambda_{adv} + \lambda_{biodiesel} \tag{3}$$

$$P_{Algal} = P_{GEth} + \lambda_{adv} + \lambda_{Algal} \tag{4}$$

where $\lambda_{adv} \geq 0$ is a price premium that applies to all advanced biofuels, and each fuel potentially enjoys its own individual premium as well. This specification reflects the nested nature of RFS2 mandates. The market excess supply of biofuels is

$$Q_{GEth} + Q_{CEth} + Q_{FAME} + Q_{Algal} - Q_{demanded} \geq 0 \perp P_{ave} \geq 0. \tag{5}$$

Here, the $\perp$ symbol denotes a complementarity relationship, whereby exactly one of either the excess supply or P_{ave} is exactly zero, and the other is strictly greater than zero.

The overall RFS (satisfied by total use of biofuels of all kinds) is imposed by requiring a minimum level of use of the biofuels bundle by the top nest of the petroleum and coal products activity. The various advanced biofuel components of RFS2 can be imposed, by allowing positive price premiums for advanced biofuels:

$$Q_{CEth} + Q_{FAME} + Q_{Algal} - RFS_{adv} \geq 0 \perp \lambda_{adv} \geq 0 \tag{6}$$

$$Q_{CEth} - RFS_{cell} \geq 0 \perp \lambda_{cell} \geq 0 \tag{7}$$

$$Q_{FAME} - RFS_{FAME} \geq 0 \perp \lambda_{Biodiesel} \geq 0 \tag{8}$$

$$Q_{Algal} - RFS_{Algal} \geq 0 \perp \lambda_{Algal} \geq 0. \tag{9}$$

Note that there is no algal component to RFS2, but we incorporate an algal price premium and the possibility of a use mandate nonetheless to facilitate evaluation of policy scenarios that feature such a mandate. Depending on the exact policy scenario under consideration, equations 4 and 8 may be modified to apply algal biofuel production to the biodiesel RFS.

Switchgrass is not currently produced in commercial quantities, and is therefore modeled as a latent technology. The cellulosic ethanol production activity is the sole consumer of aggregate biomass production from corn stover and switchgrass (if any in a given equilibrium). Biomass from these two sources commands the same price in the model in the absence of any use mandate, but switchgrass is allowed to command a price premium in the event of a binding use mandate.

$$P_{switchgass} = P_{stover} + \lambda_{switchgrass} \tag{10}$$

$$Q_{switchrass} - S \geq 0 \perp \lambda_{switchgrass} \geq 0 \tag{11}$$

Here, S is the mandated level of switchgrass use. The biomass consumer is again required to purchase biomass at a weighted average price:

$$P_{biomass} = \frac{P_{stover}Q_{stover} + P_{switchgrass}Q_{switchgrass}}{Q_{stover} + Q_{switchgrass}}. \tag{12}$$

3.4 Households

A single representative household is specified for each region. The household is endowed with primary factors of production, including land, which are rented 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 7. The household saves a portion of income and consumes a composite consumer good. This composite consumer good is produced using composite food, energy, and other goods, which are each produced in lower nests using the individual commodities represented in the model. Consumption by households is, of course, subject to sales taxes.

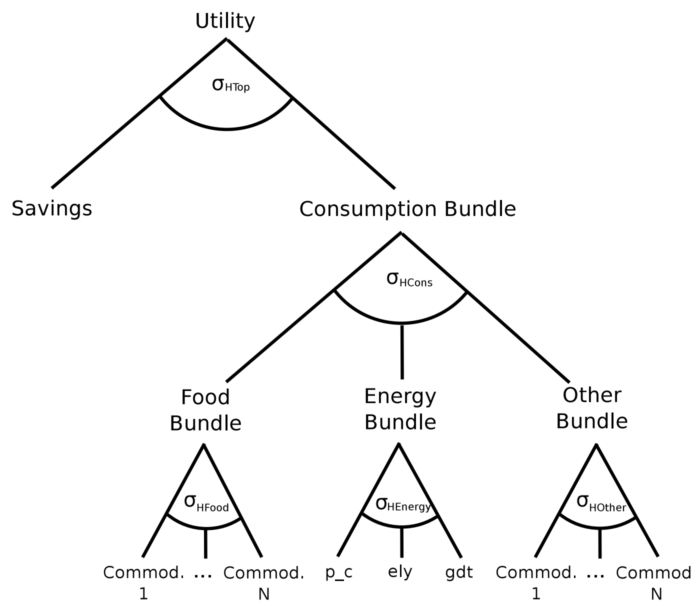

Figure 7: Household Utility Production

3.5 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 activities. Taxes are levied on 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.

3.6 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 8). 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

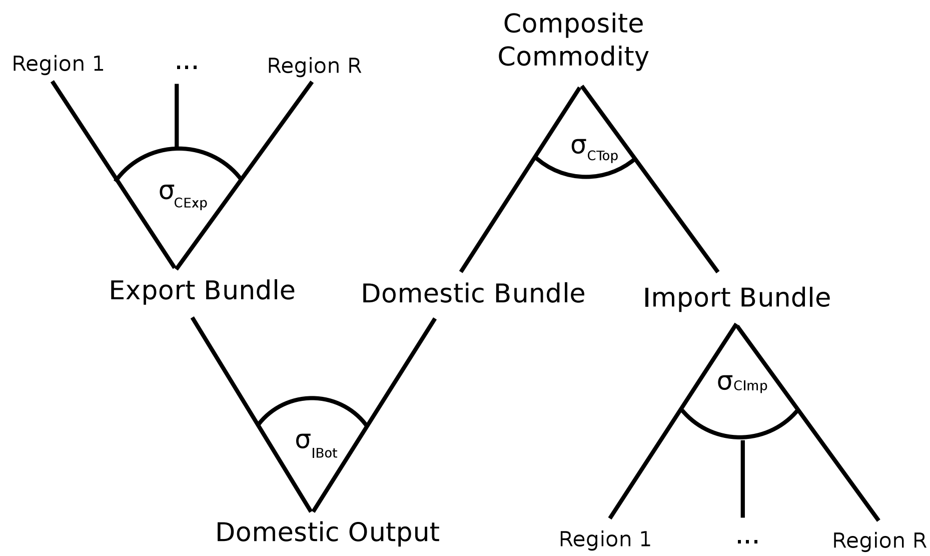

Figure 8: Commodity Trade System

that is allocated among end users.

Domestic commodity production is allocated between domestic use and export to foreign regions using nested constant elasticity of transformation (CET) functions (also depicted in Figure 8). 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 record 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.

3.7 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 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.

3.8 Model Closure

Primary factors are fully employed in each region. Government tax rates and government savings are fixed. Government spending is flexible, adjusting equi-proportionatly across consumed commodities 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 equi-proportionatly across capital goods to accommodate changes in savings.

4 Calibration of Key Elasticities of Substitution and Transformation

In this section, we describe the calibration of some of the model's constant elasticities of substitution and transformation. There are at least three approaches to calibrating elasticities of substitution. First, econometric estimates of such elasticities may be employed directly. One difficulty with this approach is finding estimates of the correct form. Blackorby and Russell (1989) demonstrate that the Morishima elasticity of substitution is the appropriate form corresponding to the standard definition of CES technology that we employ in our model, but many studies report only Allen partial elasticities of substitution.

A second approach is calibration of elasticities of substitution against demand elasticities reported in econometric studies. Similarly, elasticities of substitution can be calibrated against measured supply responses.

Finally, elasticities of substitution may be calibrated against measured yield responses (the response to output price changes of the ratio of output quantity to one specific input quantity). Because the CES production function is homogeneous of degree one, the ratio of the output quantity to any individual input quantity (a "yield" with respect to a single input such as land) is a function strictly of relative input prices. This approach therefore relies on auxiliary assumptions regarding input fixity, with Keeney and Hertel (2008) providing an example of this latter approach.

We employ the first two approaches to calibrating various elasticities of substitution and transformation in our model. Before discussing specific cases, we first describe the second approach.

4.1 Calibration of a CES to a Compensated Own-price Elasticity of Demand

The Marshallian demand function for good i associated with CES preferences is:

$$X_i^* = \frac{\alpha_i I}{p_i^\sigma \sum_j \alpha_j p_j^{1-\sigma}}$$

This can be used to generate a simplified expression for the good's compensated own-price elasticity of demand:

$$\begin{aligned}
\epsilon_{ii}^C &= \sigma \left[\frac{p_i^{1-\sigma}\alpha_i}{\sum_j \alpha_j p_j^{1-\sigma}} - 1 \right] \\
&= \sigma \left[\frac{p_i X_i^*}{I} - 1 \right] \\
&= \sigma \left[S_i - 1 \right]
\end{aligned}$$

where S_i is the income share of the ith input in the base data. Obviously, the single CES parameter σ could be calibrated against any one of the inputs' demand elasticity and income share. One simple strategy for considering information from all inputs would be to weight the individual expressions for σ by the corresponding inputs' income shares:

$$\bar{\sigma} = \sum_i S_i \left(\frac{\epsilon_{ii}^C}{S_i - 1} \right) \tag{13}$$

Note that the approach is identical in the case of CET. For CES, individual values of σ will be positive given that $S_i - 1$ must be strictly less than zero and given an $\epsilon_{ii}^C < 0$. For CET, the relevant supply responses will be positive, and individual values of σ will be negative.

4.2 Production Activities

Substitution possibilities among inputs in production activities are discussed in this subsection. In particular, our characterizations of substitution between energy and value-added inputs, between land and other inputs in production of primary agricultural commodities, and between primary resource inputs and other inputs in processing industries (e.g., petroleum refining) are described.

Energy Demand and Capital-Energy Substitution

For a model that is substantially concerned with energy-related issues, accurate reflection of energy demand and substitution between energy and other inputs in commodity and utility production is critical. Burniaux and Truong

(2002) review empirical evidence related to energy use in production activity and substitution between energy and other inputs. Taken as a whole, the body of evidence they review suggests that limited substitution between capital and energy is possible, while much greater opportunities for substitution between labor and either of capital or energy exist. This motivates the nesting structure for value-added and energy inputs into production described in Section 3 and illustrated in Figure 3. Given this nesting structure, our remaining task is to calibrate the relevant elasticities of substitution, $\sigma_{AEnergy}$, σ_{AKEn}, and σ_{AVad}.

For $\sigma_{AEnergy}$, which measures substitution possibilities among energy inputs into production, we considered several articles reviewed in Stern (2011). Noting that Stern found that elasticities of substitution tended to be smaller at higher levels of industry aggregation, Beckman and Hertel (2010) consider a subset of the studies Stern reviewed when specifying this parameter. They were concerned with calibrating a medium-run response, however, whereas we are concerned with a long-term (20 year) response. We therefore consider a smaller subset of papers in which take care to distinguish between long-run and short-run responses. The long-run own and cross price elasticities of industrial demand for energy commodities reported in Renou-Maissant (1999) suggest, on average, a value for $\sigma_{AEnergy}$ of approximately 0.35. Averaging across relevant long-run Allen partial elasticities of substitution reported in Urga (1999) and Urga and Walters (2003), a value of 0.24 is suggested. We employ the simple of average of these, specifying $\sigma_{AEnergy} = 0.305$. This is slightly higher than the 0.25 employed by Beckman and Hertel (2010), a value which they discovered would result in GTAP-E model approximately recreating energy market gyrations observed over a five-year horizon.

For σ_{AKEn}, which measures substitution possibilities between capital and energy, we review three sources. A survey in Thompson and Taylor (1995) summarizes Morishima and Allen partial elasticities of substitution from several studies conducted in the 1970s and early 1980s. They find considerable variability in the AES estaimtes, with a mean estimate of 0.17. They find the MES estimates considerably more stable, with means of 1.01 and 0.76 for the Morishima elasticities for energy and capital price changes, respectively. The MES are theoretically more appealing, and we therefore attach more weight to these estimates. Unfortunately, the data used in the reviewed studies are quite old, and no distinction is made between short and long run adjustments. Okagawa and Ban (2008) use much more recent panel data for 19 industries in 14 OECD countries to estimate nested CES production structures. Their "KE-L" nesting formulation is identical to our structure portrayed in Figure 3 without the land and natural resource components. For this structure, they find an average (across industries) value for σ_{AKEn} of 0.2125. Beckman and Hertel (2010) find that the GTAP-E model reproduces observed market activity for a five year period wen they specify a value of 0.25 for this parameter, however our horizon is somewhat longer at 20 years, affording time for greater adjustment. Considering all of the above evidence, we specify a value of 0.35 for this elasticity.

For σ_{AVad}, which measures substitution possibilities between the capital-energy composite and labor (natural resource inputs are relevant for mineral extraction activities only), we first consider the evidence from several prominent but older studies (Berndt and Wood (1975); Pindyck (1979); Kulatilaka (1980); Troung (1985)). The average partial Allen elasticity of substitution for capital and labor reported in these studies is 0.964, while the average for energy and labor is 0.848. More recently, Okagawa and Ban (2008) estimate (again using their "KE-L" nesting formulation) an average (across industries) value for σ_{AVad} of 0.35. We attach relatively more weight to recent evidence, and specify a value of 0.45 for this parameter.

Land in Agricultural Production

Elasticities of substitution between land and other inputs in agricultural commodity production will be an important determinant of land use change resulting from biofuel and energy-related shocks. We consider various direct estimates of this elasticity of substitution in specifying this model parameter.

Binswanger (1974) employs a cost function approach to estimate pairwise Allen partial elasticities of substitution between ag inputs. He pools aggregate data for agriculture for various U.S. states in 1949, 1954, 1959, and 1964. Using cost shares corresponding to his sample period, the weighted average Allen elasticity of substitution between land and other inputs is 0.802. This estimate has the disadvantages of using quite old data, and employing Allen rather than Morishima elasticities of substitution. Lopez (1980) provides also employs a dual approach, using data for Canadian agriculture for various years. For his latest sample (1977), he finds Allen partial elasticities of substitution between land and other inputs that range from 0.209 to 0.539, with an average of 0.345. Clark and Youngblood (1992) also study Canadian agriculture using a dual approach. Using their preferred model (from two separate models that they estimate), they find an average Allen partial elasticity of substitution between land and other inputs of 0.332. Debertin et al. (1990) provide estimates of Allen and Morishima elasticities for U.S. agriculture for the individual decades of the 1950's, 60's, and 70's. Using their 1970's estimates, the cost share weighted Allen partial elasticity for land vis-a-vis other inputs is 0.141. The analogous weighted average Morishima elasticity of substitution is 1.348. Hertel et al. (1996) consider substitution between land and nitrogen fertilizer in U.S. corn production. Employing time series data for 1976 through 1990, they estimate an Allen elasticity of 1.15.

Overall, these elasticity estimates exhibit little consistency, perhaps owing to varying data vintages, methodologies, and subjects of study. A simple average of the Allen elasticities of substitution cited above is 0.554, with a standard deviation of 0.41. Also troubling for specification of this parameter for our model is the fact that only a single estimate of the Morishima elasticity of substitution is available. This single estimate (1.348) is noticeably higher than our average Allen elasticity estimate, and is conspicuously higher than the corresponding Allen elasticity estimate from the same study (0.141). The time frame over which the elasticities apply is little discussed in any of the cited references.

Amid this substantial uncertainty, we specify a default value of 0.50 for this parameter. We note however that our model results in any given analysis should be subject to careful sensitivity analysis with respect to this parameter.

Processing Industries

We define processing activities as those production activities that are predominantly concerned with transformation of raw natural resources or commodities (e.g., crude oil, paddy rice, etc.) into more useful forms (e.g., petroleum products, processed rice). Here, we are primarily concerned with substitution possibilities between value-added inputs (capital and labor) and a primary intermediate input. In these production activities, we employ a very low CES of 0.15 in the production of a composite intermediate good (see Figure 6 for example) which will embody the primary raw input. Thus, substitution possibilities between the primary raw commodity input and value-added inputs are characterized predominantly by the top nest (σ_{ATop} in Figure 3).

For ag commodity processing industries, we employ estimates from Moroney and Toevs (1977). For meat packing, dairy products production, and grain milling, they find average Allen elasticities of substitution between the primary corresponding raw commodity inputs and other inputs of 0.47, 1.59, and 0.09, respectively. We map their average estimate for meat packing to our elasticity of substitution in our top level production activity nests for our beef products production activity (cmt in Table 1), our other meat products activity (omt), and our other food and beverage products activity (ofb). We map their dairy products estimate to our dairy products production activity (mil). Finally, we employ their grain milling elasticity estimate in our processed rice, processed sugar, and vegetable oil and fats activities (pcr, sgr, and vol).

Moroney and Toevs (1977) also provide estimates of partial Allen elasticities of substitution between crude oil and other inputs in petroleum refining, with an average (across paired inputs) point estimate of 0.98. We use this average estimate in our petroleum and coal products sector (σ_{ATop} in Figure 6).

4.3 Land Transformation

Here, we follow the approach of Ahmed et al. (2008), but update relevant data inputs using GTAP7 rather than GTAP6, and make modifications due to differing land transformation schemes in their work and ours. For each AEZ in our model, in the bottom CET nest depicted in Figure 4, raw land is transformed for use in either agriculture or forestry. Ahmed et al. (2008) do not provide own-return elasticities of land use for agricultural land generally, but instead provide separate own-return elasticities of land use for cropland and pastureland. We therefore calibrate this initial land transformation elasticity using their forestry own-return land use elasticity; we do not average over individual CET values as in equation 13. As depicted in Figure 2 of Ahmed et al. (2008), forestry use of land is highly inelastic, with a one-percent increase in the return to forestry land inducing only a $\approx 0.03\%$ increase in such use at a 100-year horizon. For a 20-year horizon, they indicate an own-return elasticity of forestry land use of 0.02%, which we use as a default for calibration. For the usa region, this elasticity of forestry land use and a forestry revenue share in our base year of 0.137 results in a CET for these nests in this region of -0.029. We obtain similar values for other regions.

Agricultural land is further transformed for use as either pasture or for crop production, as depicted in Figure 4. From Ahmed et al. (2008), 20-year elasticities of land use for cropland and pastureland are 0.145 and 0.345, receptively. Given that these elasticities are available for both of these uses, we employ revenue-share weighted average elasticities of transformation as in equation 13. Cropland commands a much larger share of revenue to agricultural land than does pastureland in all regions. For the usa region, we obtain individual CET values of -0.774 and -0.425 for cropland and pastureland, respectively, with a weighted average of -0.709.

4.4 Trade

The magnitudes of elasticities of substitution among imports from competing trading partners are studied in Hertel et al. (2007). These quantities correspond, in our model, to σ_{CImp} illustrated in Figure 8. We adopt their estimates, which are available for most commodities in our model. The commodities for which they are not available are electricity, water, natural gas, services, and transportation. Trade in the first three of these commodities is quite limited and difficult, relying on expensive infrastructure. We therefore assume values at the low end of the ranges for the other commodities. For services and transportation, we assume values that are typical of those for other commodities.

The elasticities of substitution between imported and domestically produced commodities will also be an important determinant of the response of trade patterns to shocks (σ_{CTop} in Figure 8). For key commodities, we calibrate these elasticities against various econometric estimates.

4.5 Substitution between Petroleum Fuels and Biofuels

Reliable econometric measurements for calibrating this elasticity of substitution ($\sigma_{ANewTop}$ in Figure 6) are not available. Rapid increases in the use of biofuels in the U.S. and Europe in recent years suggest a substantial societal willingness to incorporate biofuels into the overall liquid fuel mix. Hertel et al. (2010) exploit this recent experience to infer values for this parameter, adjusting it until their CGE model accurately reproduced observed changes in biofuel consumption between 2001 and 2007. They find a value of 1.65 for the E.U. and a value of 3.95 for the U.S. Due to the time required for vehicle fleets to adjust to accommodate alternative fuels, this parameter should be specified with consideration of the adjustment horizon of a particular analysis. A 20-year adjustment horizon should afford somewhat greater flexibility than the values inferred using 2001-2007 data; we set a default value of 4.0 for this parameter.

5 Calibration of Biofuels and Energy Crop Production Sectors

5.1 Calibration of Ethanol-related Sectors

Calibration of the grain ethanol production function is accomplished by calibrating cost shares and total cost to available cost studies. 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 schedules were adjusted to reflect a 2004 corn price (corresponding to our GTAP7 base year). The average adjusted unit cost estimate of about \$1.21 is employed in calibration. Cost shares for individual inputs were averaged over available studies as well, and those averages were used for calibration. Actual per gallon unit costs are used as the base year price rather than unity, and the corresponding output quantity variables are therefore measured in standard physical units (i.e., gallons).

All available cost estimates for cellulosic ethanol production assume use of switchgrass as a feedstock (Aden et al., 2002; McAloon et al., 2000; Wallace et al., 2005; Wooley et al., 1999), and these cost data are used for calibration. The different cost estimates are normalized to reflect identical biomass costs, and to reflect the cost of biomass collection and transportation. 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 these categorized costs were mapped to the primary factors and commodities employed in the model. As with the grain ethanol production sectors, per gallon unit costs are used as the base year price rather than unity, and the corresponding output quantity variables are therefore measured in gallons.

We incorporate a dedicated switchgrass production activity following the approach taken by McDonald et al. (2006), and contrasting 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. The specification of cost shares for individual AEZ land inputs is based on comparison of the geographical distribution of U.S. AEZ endowments (see Figure 1) with the geographical distribution of likely switchgrass production reported in Ugarte et al. (2003). This approach considers both the suitability of individual AEZs for switchgrass production and the returns of competing uses of land in each AEZ. The total 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

Table 2: Cost Structures of Ethanol-related Production Activities

	U.S. Grain Ethanol ($/gal)	U.S. Cellulosic Ethanol ($/gal)	U.S. Switchgrass ($/ton)
Capital	0.21	0.52	9.99
Labor	0.11	0.25	10.41
Biomass		0.77	
AEZ7			0.22
AEZ8			8.84
AEZ9			8.84
AEZ10			1.11
AEZ11			1.11
AEZ12			1.99
Other cereal grains	0.47		
Other crops			1.03
Other mineral mining			0.46
Textiles and clothing products			0.46
Wood and paper products			0.05
Petroleum and coal products	0.08	0.02	1.37
Chemical rubber and plastic products	0.09	0.29	
Other manufactured products			19.52
Electricity	0.07	0.02	
Gas manufacturing and distribution	0.05		
Water	0.01	0.01	
Transportation	0.12	0.20	
Total	1.21	2.08	65.39

from these sources were adjusted based on their varying assumptions, and a average price of approximately $65 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 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).

5.2 Calibration of Biodiesel-related Sectors

Two biodiesel-related sectors are incorporated into the model. The fatty acid methyl ester (FAME) production activity is based on a vegetable oil feedstock. This sector is calibrated against the cost structure reported in Fortenbery (2005) for an operation using soybean oil as a feedstock. Individual cost items were not adjusted to reflect 2004 prices, as that research likely took place predominantly in 2004 (corresponding to our GTAP7 base year). The unit cost estimate of about \$2.88 per gallon is employed in calibration. Actual unit costs per 84,000 BTU of biodiesel are used as the base year price, and the corresponding output quantity variables in our model are therefore measured in ethanol energy-equivalent volumes (cf., gallons or non-standard units that imply a base-year price of unity). The cost structure for vegetable oil FAME is presented in Table 3. For this vegetable oil biodiesel activity we employ a nested CES strucutre similar to the standard production technology (Figure 3). However, this activity features vegetable oil as an individual input into the top nest (it is not included in the intermediate nest), and no composite land input. This allows us to specify a very limited potential for substitution between the feedstock and other inputs ($\sigma_{Top} = 0.15$).

Calibration of the algal biodiesel production activity is much more challenging, as no commercial scale production exists, and eventual production costs are highly uncertain. We currently have available three full cost structure estimates, any of which can be employed in our model.

Allison (2010) considers the construction and operation of a commercial scale (hundreds of acres) open pond algal production system in either Texas or New Mexico. His analysis includes harvesting and extraction processes, and he reports output of algal oil, algal meal and high-value oils. His study employs vendor quotes to develop original cost estimates, and considers net influences on profitability to optimize some aspects of the operation's design (especially water depth). He also considers the effect of stochastic growing conditions, and costs per unit of output therefore vary with weather conditions. We employ 10-year average costs from his model for algal oil production in New Mexico to calculate costs per 84,000 BTU of final diesel fuel. We assume a standard transesterification process is applied to the algal oil. We adjust all production costs to a 2004 basis (corresponding to the base year for the GTAP7 data) using various producer price indexes from BLS. These adjusted costs, mapped to WEAM commodities and primary factors, are reported in Table 3. We use a hypothetical 2004 price for algal meal from Gogichaishvili (2011) in calculating co-product value.

Davis (2011) evaluates the feasibility of building and operating a facility that would produce 10 million gallons per year of algal oil, using either open ponds or photobioreactor technology (hence we acquire two cost estimates from this source). Lipid content is assumed to be around 35%, and high-value oil output is not considered. Productivity of 0.11 grams of biomass per liter of water per day is assumed. They estimate capital costs for open pond and photobioreactor systems using a combination of vendor quotes, previous estimates, and standard engineering estimates. We again assume a standard transesterification process is applied to the algal oil. Total costs, adjusted to a 2004 basis and mapped to WEAM commodities and primary factors, are reported in Table 3. The photobioreactor approach is dramatically more expensive at \$24.44 (2004 costs) per 84,000 BTU of fuel, with a comparable cost for the open pond approach of

Table 3: Cost Structures of Biodiesel-related Production Activities

	Veg-oil FAME ($/84KBTU)	Algal FAME Davis (pond) ($/84KBTU)	Algal FAME Davis (PBR) ($/84KBTU)	Algal FAME Allison (pond) ($/84KBTU)
Capital	0.1249	7.8607	20.6144	14.8446
Labor	0.1068	0.9876	2.2192	1.3350
Vegetable Oil	1.4345			
Electricity	0.0001	0.0001	0.2940	0.5970
Natural gas	0.0362	0.0972	0.1033	0.6039
Petroleum and coal prod.	0.0790	0.0790	0.0790	0.0790
Chemicals, rubber & plastic	0.0215	1.3890	1.0486	0.4316
Services	0.0399	0.2085	0.0512	0.0399
Transportation	0.0323	0.0323	0.0323	0.0323
Total Cost	1.8752	10.6543	24.4420	17.9633
Co-product value				0.7989

$10.65.

6 Food Insecurity Analysis

Changes in equilibrium levels of market variables, including final consumption of food commodities, are determined in calculated equilibria, and food insecurity calculations can follow from a second stage analysis. For this second stage, we adopt the UN Food and Agriculture Organization (FAO) method for estimating changes in the numbers of food insecure people. This method of coupling our CGE to the FAO caloric distributions is very similar to that of Bach and Matthews (1999).

The FAO method for estimating changes in the numbers of food insecure people as aggregate consumption of food commodities changes is described in Naiken (2002). The FAO measure endeavors to capture those whose food consumption level is insufficient for body weight maintenance and work performance, focusing on the phenomenon of hunger rather than poor nutrition. The FAO measure of food insecurity is based on a probability distribution framework. Given the distribution of dietary energy consumption $f(x)$ within a region, the percentage of undernourished people is estimated as the proportion of population below the minimum per capita dietary energy requirement r_L. This arrangement is illustrated in Figure 9. r_L is derived by aggregating the estimated gender and age-specific minimum dietary energy requirements, using the relative proportions of a population in the corresponding sex-age group as

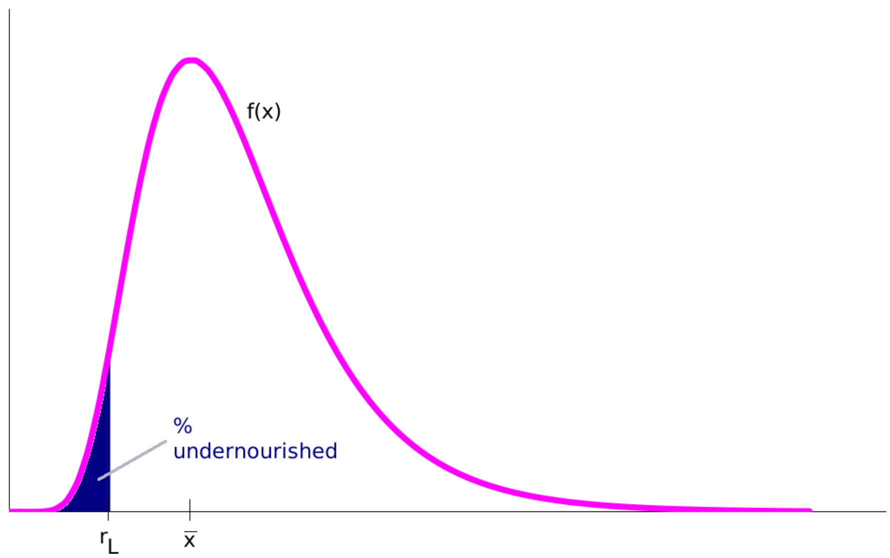

Figure 9: FAO Method of Calculating the Number of Undernourished People in a Region.

weights. The estimates are calculated on a country-by-country basis and are reported periodically by FAO.

The distribution $f(x)$ is estimated based on household surveys, which collect data on the quantities of food product consumed by individuals in a representative sample of households in the population. However, the methodology and concepts applied in the surveys are not sufficiently precise to provide an accurate and reliable estimate of the distribution, and FAO therefore employs a theoretical distribution. The frequency distributions suggested by the food survey data are generally unimodal, and FAO considered a specific group of appropriate distributions.

FAO initially employed the Beta distribution, as it enabled fixing the lower and upper limits of the range as determined by the physiological lower and upper limits of intake in individuals. However, researchers found this distribution was appropriate only when dealing with the true intake of individuals. In most of the surveys, the data refer to the food available to, or acquired by, the household and thus include household wastage, food fed to pets, etc. Since 1987, FAO has instead employed the two-parameter log-normal distribution. The short lower tail and long upper tail better reflect the richer and more affluent households, who are more likely to have wastage and food fed to pets.

The log-normal distribution can be specified by two parameters, the coefficient of variations $CV(x)$, and the mean $(\overline{x})$. Given these two parameters, the mean and variance of the corresponding normal distribution can be determined as

$$\sigma^2 = ln\left(CV^2(x) + 1\right)$$

and

$$\mu = \frac{ln(\overline{x}) - \sigma^2}{2}.$$

The $CV(x)$ is estimated as

$$CV(x) = \sqrt{CV^2(x|v) + CV^2(x|r)}$$

where $CV(x|v)$ is variation owing to household per capita income, v, and $CV(x|r)$ is variation due to the energy requirement r. A detailed procedure of estimation is documented in Naiken (2002). Because the inequality of income distribution for a number of developing countries varied little over the last three decades, and the inequality in the distribution of household per capita food consumption is much smaller than the inequality in the distribution of household income, $CV(x)$ is assumed to be constant year-to-year between surveys.

The mean $\overline{x}$ represented by the per capita dietary energy supply refers to the energy available for human consumption, expressed in kilo-calories (kcal) per person. It is derived from the food balance sheets (FBS) compiled every year by FAO on the basis of data on the production and trade of food commodities. The total dietary energy supply is obtained by aggregating the food component of all commodities after being converted into energy values.

Energy requirements are different for different individuals. The most influential factors are age, sex, body weight, and activity level. The r_L for a country is derived by aggregating the minimum sex-age-specific energy requirement with information on the composition of the population.

The sex-age-specific energy requirement is derived in two procedures. For adults and adolescents, the energy requirements are calculated with the basal metabolic rate (BMR). For children below age ten, the energy requirements are expressed as fixed amounts of energy per kilogram of body weights. The lower limits of the requirements for each sex-age group were derived with the lowest acceptable body weight and lowest acceptable activity allowance. r_L is around 2,000 kcal per day for each country, and is updated by FAO periodically as the composition of populations change over time.

FAO provides caloric intake distributions for a much larger number of countries/regions than are featured in the CGE model. To estimate the daily calorie intake distribution for each of nine aggregate regions that correspond to the regions of the CGE model, we adopted a two-step Monte Carlo simulation method. First we randomly draw a country i within the region with probabilities equal to the population weights. We then randomly draw a number from the specific country's distribution $f_i(x)$. We employ 65,500 trials for each aggregate region to estimate its empirical aggregate caloric intake distribution $f(x)$. While we take care to accommodate the possibility of complex aggregate caloric intake distributions, all nine of the simulated aggregate distributions appear unimodal with an approximate log-normal shape. Within each region, the per capita dietary energy supply for each country is aggregated by the population weights, using the 2004 Food Balance Sheets. Per capita dietary energy supply from each food group in our model is also aggregated in the same way.

Similarly, the lowest energy requirement level r_L is aggregated with population weights of the countries within the specific region. With the daily calorie intake distribution $f(x)$ and the lowest energy requirement level (r_L) for each region, we can update the mean $\overline{x}$ corresponding to the results from the CGE model, and calculate the proportion of undernourished people within each region for different scenarios.

References

Aden, A., Ruth, M., Ibsen, K., Jechura, J., Neeves, K., Sheehan, J., Wallace, B., Montague, L., Slayton, A., and Lukas, J. (2002). Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. Technical Report NREL/TP-510-32438, National Renewable Energy Laboratory, 1617 Cole Boulevard Golden, Colorado 80401-3393.

Ahmed, A., Hertel, T., and Lubowski, R. (2008). Calibration of a land cover supply function using transition probabilities. GTAP Research Memorandum 12, Center for Global Trade Analysis, Purdue University.

Allison, M. (2010). The future of biofuels: An economic analysis of the design and operation of a microalgae facility in texas and the southwestern united states. Master's thesis, Texas A&M University.

Armington, P. S. (1969). A theory of demand for products distinguished by place of production. *International Monetary Fund Staff Papers*, 16:159–176.

Bach, C. and Matthews, A. (1999). Development aid and food security. In *Second Annual Conference on Global Economic Analysis*, pages 20–22, Avernaes, Denmark.

Beckman, J. F. and Hertel, T. W. (2010). Validating energy-oriented CGE models. GTAP Working Paper 54, Global Trade Analysis Project, Department of Agricultural Economics, Purdue University.

Berndt, E. R. and Wood, D. O. (1975). Technology, prices, and the derived demand for energy. *Review of Economics and Statistics*, 57(3):259–268.

Binswanger, H. P. (1974). A cost function approach to the measurement of elasticities of factor demand and elasticities of substitution. *American Journal of Agricultural Economics*, 56:377–386.

Blackorby, C. and Russell, R. R. (1989). Will the real elasticity of substitution please stand up? *American Economic Review*, 79:882–888.

Burnes, E., Wichelns, D., and Hagen, J. W. (2005). Economic and policy implications of public support for ethanol production in California's San Joaquin valley. *Energy Policy*, 33:1155–1167.

Burniaux, J.-M. and Truong, T. P. (2002). GTAP-E: An Energy-Environmental Version of the GTAP Model. GTAP Technical Paper 16, Center for Global Trade Analysis, Purdue University, West Lafayette, Indiana 47907-1145.

Clark, J. S. and Youngblood, C. E. (1992). Estimating duality models with biased techincal change: a time series approach. *American Journal of Agricultural Economics*, 74:354–360.

Davis, R. (2011). Techno-economic analysis of autotrophic microalgae for fuel production. *Applied Energy*, 88:3512–3531.

Debertin, D. L., Pagoulatos, A., and Aoun, A. (1990). Impacts of technological change on factor substitution between energy and other inputs within US agriculture, 1950-79. *Energy Economics*, 12(1):2–10.

Duffy, M. (2008). Estimated costs for production, storage and transportation of switchgrass. Online Decision Tool. File A1-22.

Duffy, M. D. and Nanhou, V. Y. (2002). Costs of producing switchgrass for biomass in Southern Iowa. In Janick, J. and Whipkey, A., editors, *Trends in new crops and uses*, pages 267–275. ASHS Press, Alexandria, VA.

Eidman, V. R. (2007). Economic parameters for corn ethanol and biodiesel production. *Journal of Agricultural and Applied Economics*, 39(2):345–356.

Environmental Protection Agency (2007). Regulatory impact analysis: Renewable fuel standard program chapter 7 estimated costs of renewable fuels, gasoline and diesel. Technical Report EPA420-R-07-004, Assessment and Standards Division Office of Transportation and Air Quality US Environmental Protection Agency.

EPA (2010a). EPA finalizes regulations for the national Renewable Fuel Standard program for 2010 and beyond. U.S. Environmental Protection Agency Regulatory Announcement EPA-420-F-10-007.

EPA (2010b). EPA lifecylce analysis of greenhouse gas emmisions from renewable fuels. U.S. Environmental Protection Agency Regulatory Announcement EPA-420-F-10-006.

Fortenbery, T. R. (2005). Biodiesel feasibility study: An evaluation of biodiesel feasibility in Wisconsin. Staff Paper No. 481, University of Wisconsin-Madison, Department of Agricultural & Applied Economics.

Gallagher, P. W., Dikeman, M., Fritz, J., Wailes, E., Gauthier, W., and Shapouri, H. (2003). Supply and social cost estimates for biomass from crop residues in the United States. *Environmental and Resource Economics*, 24:335–358.

Gehlhar, M., Gray, D., Hertel, T. W., Huff, K. M., Ianchovichina, E., McDonald, B. J., McDougall, R., Tsigas, M. E., and Wigle, R. (1997). *Overview of the GTAP data base*, chapter 3, pages 74–123. Cambridge University Press.

Gogichaishvili, I. (2011). Application of hedonic price modeling to estimate the value of algae meal. Master's thesis, Texas A&M University.

Hertel, T., Hummels, D., Ivanic, M., and Keeney, R. (2007). How confident can we be of cge-based assessments of free trade agreements? *Economic Modelling*, 24:611–635.

Hertel, T., Tyner, W., and Birur, D. (2010). The global impacts of biofuel mandates. *The Energy Journal*, 31(1):75–100.

Hertel, T. W., Stiegert, K., and Vroomen, H. (1996). Nitrogen-land substitution in corn production: a reconciliation of aggregate and firm-level evidence. *American Journal of Agricultural Economics*, 78:30–40.

Hettenhaus, J. R. and Wooley, R. (2000). Biomass commercialization propects in the next 2 to 5 years biomass colloquies 2000. Subcontractor Report NREL/ACO-9-29-039-01, National Renewable Energy Laboratory U.S. Department of Energy, 1617 Cole Boulevard Golden, Colorado 80401-3393.

Keeney, R. and Hertel, T. W. (2008). The indirect land use impacts of U.S. biofuel policies: the importance of acreage yield, and bilateral trade responses. GTAP Working Paper 52, Global Trade Analysis Project, Department of Agricultural Economics, Purdue University.

Khanna, N. and Chapman, D. (2001). *Energy Efficiency and Petroleum Depletion in Climate Change Policy.* JAI Press.

Kulatilaka, N. (1980). A partial equilibrium model of derived demand for production factor inputs. Working Paper 1176-80, Alfred P. Sloan School of Management, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Lee, H., Hertel, T., Rose, S., and Avetisyan, M. (2009). An integrated global land use data base for CGE analysis of climate policy options analysis of climate policy options. In Thomas W. Hertel, S. K. R. and Tol, R. S., editors, *Economic analysis of land use in global climate change policy*, chapter 4. Routledge, London and New York.

Lopez, R. E. (1980). The structure of production and the derived demand for inputs in Canadian agriculture. *American Journal of Agricultural Economics*, 62:38–45.

Lundquist, T. J., Woertz, I. C., Quinn, N. W. T., and Benemann, J. R. (2010). A realistic technology and engineering assessment of algae biofuel production. Technical report, Energy Biosciences Institute, University of California, Berkeley, California.

Mapemba, L. D., Epplin, F. M., Taliaferro, C. M., and Huhnke, R. L. (2007). Biorefinery feedstock production on conservation reserve program land. *Review of Agricultural Economics*, 29(2):227–246.

McAloon, A., Taylor, F., Yee, W., Ibsen, K., and Wooley, R. (2000). Determining the cost of producing ethanol from corn starch and lignocellulosic feedstocks. Technical Report NREL/TP-580-28893, National Renewable Energy Laboratory, 1617 Cole Boulevard Golden, Colorado 80401-3393.

McDonald, S., Robinson, S., and Karen Thierfelder, K. (2005). A SAM based global CGE model using GTAP data. Sheffield Economic Research Paper 2005001, Department of Economics, University of Sheffield.

McDonald, S., Robinson, S., and Thierfelder, K. (2006). Impact of switching production to bioenergy crops: The switchgrass example. *Energy Economics*, 28:243–265.

McDonald, S. and Thierfelder, K. (2004). Deriving a global social accounting matrix from GTAP versions 5 and 6 data. GTAP Technical Paper 22, Global Trade Analysis Project, De. Scott McDonald Department of Economics The University of Sheffield 9 Mappin Street Sheffield, S7 1HR, UK.

McFarland, J. R., Reilly, J., and Herzog, H. J. (2004). Representing energy technologies in top-down economic models using bottom-up information. *Energy Economics*, 26(4):685–707.

Monfreda, C., Ramankutty, N., and Hertel, T. W. (2009). Global agricultural land use data for climate change analysis. In Hertel, T. W., Rose, S. K., and Tol, R. S., editors, *Economic Analysis of Land Use in Global Climate Change Policy*, chapter 3. Routledge, London and New York.

Moroney, J. R. and Toevs, A. L. (1977). Factor costs and factor use: an analysis of labor, capital, and natural resource inputs. *Southern Economic Journal*, 43:222–239.

Naiken, L. (2002). FAO methodology for estimating the prevalence of undernourishment. In *Proceeedings of the International Scientific Symposium on Measurement and Assessment of Food Deprivation and Undernutrition*. Food and Agricultural Organization of the United Nations. Available online at http://www.fao.org/docrep/005/Y4249E/y4249E00.HTM.

Okagawa, A. and Ban, K. (2008). Estimation of substitution elasticities for CGE models. Technical Report Discussion Paper 08-16, Graduate school of economics and Osaka school of international public policy, Osaka, Japan.

Perrin, R., Vogel, K., Schmer, M., and Mitchell, R. (2008). Farm-scale production cost of switchgrass for biomass. *BioEnergy Research*, 1:91–97.

Perrin, R., Voggel, K., Schmer, M., and R. Mitchell, R. (2003). Switchgrass – a biomass energy crop for the Midwest. Technical report, North Dakota State University Central Grasslands Research Extension Center.

Pindyck, R. S. (1979). *The structure of world energy demand*. The MIT Press, Cambridge, Massachusetts.

Raneses, A., Hanson, K., and Shapouri, H. (1998). Economic impacts from shifting cropland use from food to fuel. *Biomass and Bioenergy*, 15(6):417–422.

Reilly, J. M. and Paltsev, S. (2007). Biomass energy and competition for land. Technical Report Report No. 145, MIT Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Renou-Maissant, P. (1999). Interfuel competition in the industrial sector of seven OECD countries. *Energy Policy*, 27:99–110.

Shapouri, H. and Gallagher, P. (2005). USDA's 2002 ethanol cost-of-production survey. Agricultural Economic Report 841, United States Department of Agriculture Office of Energy Policy and New Uses.

Shoven, J. B. and Whalley, J. (1992). *Applying General Equilibrium*. Cambridge University Press, Cambridge, United Kingdom.

Stern, D. I. (2011). Interfuel substitution: a meta-analysis. *Journal of Economic Surveys*, forthcoming:DOI: 10.1111/j.1467–6419.2010.00646.x.

Thompson, P. and Taylor, T. G. (1995). The capital-energy substitutability debate: a new look. *Review of economics and statistics*, 77(3):565–569.

Tiffany, D. G. and Eidman, V. R. (2003). Factors associated with success of fuel ethanol producers. Staff Paper P03-7, Department of Applied Economics College of Agricultural, Food, and Environmental Sciences University of Minnesota, August.

Tiffany, D. G., Morey, R. V., and Kam, M. D. (2008). Use of distillers by-products and corn stover as fuels for ethanol plants. Prepared for presentation at the conference entitled, Transition to a Bioeconomy: Integration of Agricultural and Energy Systems, which was sponsored by the Farm Foundation, in Atlanta, Georgia.

Troung, T. P. (1985). Inter-fuel and inter-factor substitution in NSW manufacturing industry. *Economic Record*, 61(3):644–653.

Turhollow, A. (2000). Cost of producing biomass from riparian buffer strips. Technical Report ORNL/TM-1999/146, Energy Division Oak Ridge National Laboratory, Oak Ridge National Laboratory Oak Ridge Tennessee 37831-6285.

Ugarte, D., Walsh, M. E., Shapouri, H., and Slinsky, S. P. (2003). The economic impacts of bioenergy crop production on U.S. agriculture. Technical Report Agricultural Economic Report Number 816, United States Department of Agriculture, Washington, D. C.

Urga, G. (1999). An application of dynamic specifications of factor demand equations to interfuel substitution in US industrial energy demand. *Economic Modelling*, 16:503–513.

Urga, G. and Walters, C. (2003). Dynamic translog and lineal logit models: a factor demand analysis of interfuel substitution in US industrial energy demand. *Energy Economics*, 25:1–21.

Vogel, K. P. (2007). Switchgrass for biomass energy: Status and progress. Presentation at the USDA Agricultural Outlook Forum, March 1, 2007.

Wallace, R., Ibsen, K., McAloon, A., and Yee, W. (2005). Feasibility study for co-locating and integrating ethanol production plants from corn starch and lignocellulosic feedstocks. Technical Report NREL/TP-510-37092 USDA-ARS 1935-41000-055-00D, National Renewable Energy Laboratory, 1617 Cole Boulevard Golden, Colorado 80401-3393.

Walsh, M. E., Ugarte, D. G. D. L. T., Shapouri, H., and Slinsky, S. P. (2003). Bioenergy crop production in the United States. *Environmental and Resource Economics*, 24:313–333.

Wijffels, R. H. and Barbosa, M. J. (2010). An outlook on microalgal biofuels. *Science*, 329:796–799.

Wooley, R., Ruth, M., Sheehan, J., Ibsen, K., Majdeski, H., and Galvez, A. (1999). Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis curren and futuristic scenarios. Technical Report NREL/TP-580-26157, National Renewable Energy Laboratory, 1617 Cole Boulevard Golden, Colorado 80401-3393.