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Abstract

In the late 2000s, the world grain markets experienced severe turbulence with rapid crop price rises caused by bad crops, oil price hikes, export restrictions, and the emergence of biofuels as well as financial speculation. We review the impacts of the first four real-side factors using a world trade computable general equilibrium model. Our simulation results show that oil and biofuels-related shocks were the major factors among these four in crop price hikes but that these real-side factors in total can explain only about 10% of the actual crop price rises.

Keywords

food crisis; crop price hikes; bad crops; oil price hikes; export restrictions; emergence of biofuels; computable general equilibrium model

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1. Introduction

1.1 Causes and Consequences of the Commodity Boom

The world crop markets experienced significant turbulence before and after the financial crisis that occurred in 2008. Rice, wheat, and maize prices had quadrupled, tripled, and doubled, respectively before the bubble burst (Figure 1). After the financial crisis, however, their prices reverted to the levels observed in 2005, except for rice, whose price hike was only halved. The price hikes can be attributed to several factors: bad crops, cost-push by the oil price hike, demand increase for biofuels production, restrictions on crop exports, and speculation.

Bad crops hit several major wheat producers. Australia, which covers 16% of world wheat exports in 2004, had a streak of bad harvests losing 44% and 36% of its wheat output in 2006 and 2007, respectively, compared with that in 2004. Ukraine, the ninth largest exporter with a 2% share of the world's wheat exports, also had a very poor crop season in 2007.

In the mid-2000s, oil prices had steadily risen and tripled to push up prices of various goods due to production costs. This led major crop-producing countries to explore biofuels as substitutes for conventional fossil fuels. The world's biofuels production increased very rapidly in this period. The EU (producing biodiesel from oilseeds), the US and Brazil (producing bioethanol from maize and sugarcane), and others produced 46.5 million liters of crude oil equivalent biofuels in 2007. This is, however, negligibly small compared with the total crude oil supply. This commitment to biofuels caused more severe competition for food crops between food consumption and energy uses.

In reaction to the crop price hikes, some countries restricted their crop exports to secure their domestic supply (Table 1), triggering crop prices spikes (Figure 1). The countries that resorted to these export restrictions supply about 43% of rice and 19% of wheat in their international markets. As rice has a very thin international market, its market price was much more volatile than that of other crops.

1.2 Literature Review

The market turbulence was indeed dramatic. Many studies have tried to uncover the factors behind the 2008 food crisis. Debate is still keen. Heady and Fan (2008) as well as Timmer (2008) attribute the causes to various factors that are commonly recognized, such as increasing food demand in China and India, speculation, export restrictions, short-run or long-run productivity, depreciation of the US dollar, oil prices, biofuels, and the decline of stocks. Wright (2011) rejects all but the combination of the last two by emphasizing the role of stock demand, which arises only in low price periods.[1]

Yang et al. (2008) investigate the impact of the petroleum price hike and an increase of biofuels production using a computable general equilibrium (CGE) model, based on the Global Trade Analysis Project (GTAP) database version 6 (Table 2).[2] Mitchell (2008) examines its impacts on the production cost of wheat and maize production in the US and their domestic transportation costs. Charlesbois (2008) estimates the influence of export restrictions on crops using a multi-country dynamic partial equilibrium model. Rosegrant (2008) measures the impacts of biofuels production on these crops using a partial equilibrium model by assuming different biofuel production growth rates. Yang et al. (2008) also quantify its impact on prices of wheat and maize and find similar results to those by Rosegrant (2008). These studies consistently show real-side factors have only limited explanatory power for the crop price hikes. Du et al. (2011) examine the financial aspect of the crop market with the futures markets data and find that volatility spillovers among

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[1] Wright (2011) considers two types of demand: demand for consumption and for stocks. Following the "buy low, sell high" rule, the stock demand arises only when the price and the stock level are low. Only consumption demand, which is supposed to be less price elastic than the stock demand, remains when the price is high.

[2] See Hertel (1997) for the GTAP database and its standard CGE model and Burniaux and Truong (2002) for the GTAP-E model.

crude oil, maize, and wheat prices significant in the boom period. This is similar to the finding by Roache (2010), inferring that the oil-crop linkage has become important through the recent emergence of biofuels. Cooke and Robles (2009) also attribute the price rise to speculator factors by their time series analysis.

The earlier studies on those real-side factors, however, do not consider the crop failure of wheat in Australia and/or Ukraine in the latter half of the 2000s. The rice sector has not been analyzed in the context of the recent food crisis or petroleum price hikes. Rosegrant's (2008) analysis of the biofuels' impact does not reach 2008, when the grain prices rose most severely. The partial equilibrium models used by Rosegrant (2008) and Charlesbois (2008) do not describe any linkages among crop and food markets through intermediate input demand and their substitution in consumption. Biofuels are also used as a substitute for fossil fuels to ease the oil price rise while causing food shortages through competition in the food markets. Although Yang et al. (2008) model the competition among crops and biofuels for farm-land assuming its flexible reallocation among crops, the farm-land switching was not conspicuous in recent years (Figure 2).

We need further and more detailed examinations of the impacts of the crop market turbulence with a comprehensive framework of the world trade CGE model that enables us to capture the interaction among markets by alternatively assuming such factors and situations that the earlier studies do not consider. We simulate various real-side shocks observed in the latter half of the 2000s to investigate what factors caused the crop price hikes and to what extent these real-side factors can explain the hikes. Using a static CGE model with inter-sectoral immobility of farm-land, we focus on short-run phenomena marked especially during the recent food crisis period.

This paper proceeds as follows. Section 2 explains our CGE model and simulation scenarios for our decomposition analysis of the price hike factors. Section 3 shows our simulation results, followed by the concluding Section 4.

2. Model and Simulation Scenarios

2.1 Model Structure

A single-country CGE model used in Devarajan et al. (1990) is extended to a multi-country model for this study, à la Hosoe et al. (2010, Ch. 10). We use the GTAP database version 7.1, whose reference year is 2004. Regions are aggregated so that we can focus on major producers of grains and biofuels (Table 3). To describe biofuels in our model, we newly distinguish three sectors important for biofuels (maize, bioethanol, and biodiesel) other than the original 11 sectors in the GTAP dataset by using a technique similar to the one that Taheripour et al. (2008) use.[3]

Each sector has a perfectly competitive profit maximizing firm with Leontief production function for gross output (Figure 3).[4] While labor is mobile among sectors, capital stocks, farmland, and natural resources are assumed to be immobile among sectors. The value-added composite made of these primary factors is combined with intermediate inputs and an energy composite to produce gross output, which is allocated between domestic good supply and composite exports by a constant elasticity of transformation (CET) function. The composite exports are further decomposed into outbound shipping to individual regions with a CET technology. Similarly, the domestic goods and composite imports made of inbound shipping from various regions are combined into composite goods with a constant elasticity of substitution (CES) function following Armington (1969). The composite imports are generated with imports shipped from various regions. The elasticities of the CES and CET functions of imports and exports are quoted from the GTAP database. The energy composite is made of non-liquid energy inputs (coal, gas, and electricity) and a liquid energy composite with a Cobb-Douglas technology.[5] The liquid energy composite is

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[3] Details are described in Appendix I.

[4] The model equations are described in Appendix II.

[5] As Burniaux and Truong (2002) assume that the elasticity of substitution among energy inputs is 0.5 or 1.0 in the GTAP-E model, we follow their assumption.

also made of liquid energy inputs (oil, bioethanol, and biodiesel) with a CES technology.[6]

A representative household maximizes its utility subject to its budget constraints. Consumption is determined by two-stage budgeting (Figure 4). First, the household considers a trade-off among various food-related goods. Its food consumption is aggregated into a food composite with a CES function, whose elasticity of substitution is assumed to be 0.1, following Tanaka and Hosoe (2011). At the top stage, the household considers a trade-off among the food composite and the other goods. The household determines its energy use in the same manner that industries do with a nested CES aggregation. The other domestic final demand (government and investment) is kept constant while their expenses are supported by lump-sum transfers from the household in the forms of a direct tax and savings.

2.2 Simulation Scenarios

The four types of shocks are considered individually in Scenarios C, R, P, and B. The fifth Scenario A considers all four at once (Table 4). Even if we take account of all these four major real-side factors in Scenario A, the estimated price rises of these crops will fall short of the actual price rise. This gap could be attributed to non-real-side factors, i.e., speculation. To compute the magnitude of the crop price hikes, the nominal international prices of crops and crude oil reported in the IMF Primary Commodity Prices are deflated with the global inflation data reported in the IMF's World Economic Outlook. The price rise

[6] The elasticity of substitution for the liquid energy aggregation function is set to be two, assuming these liquid energy inputs are a closer substitute than the liquid and the non-liquid inputs. We conducted a sensitivity analysis with respect to the elasticity of substitution for these two energy input aggregation functions and found our results to be robust, as summarized in Appendix III.

in wheat, rice, and maize are estimated to be 87%, 165%, and 79% during 2004–2008.[7]

In Scenario C (Crop failures), we simulate the bad wheat crops in Australia and Ukraine that occurred in 2007 (Table 1).[8] These shocks are given to the total factor productivity parameter in the gross output production function (Figure 3). Scenario R (export Restrictions) captures the impact of the export restrictions on crops. While many countries set some type of export restrictions such as bans, quotas, and taxes, we focus on the actions by the six major countries with market shares larger than 1% of the world exports.[9] We assume a 95% cut of exports as an approximation of export bans to avoid computational difficulty in our CGE model, where a nested CES structure is used to describe the bilateral trade patterns. In Scenario P (Petroleum), an oil price hike of 126% is assumed. This price rise is generated by imposition of export taxes on crude oil at the same rate by all oil exporters. Scenario B (Biofuels) is designed to evaluate the impact of bioethanol production from maize and sugarcane in the US and Brazil, respectively, and that of biodiesel production from oilseeds in the EU. We set the bioethanol and biodiesel production at the actual level in 2008 leveraged by production subsidies for these two sectors.

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[7] The IMF Primary Commodity Prices reports export prices of the world's largest exporters as the world market prices. That is, the world prices of wheat, rice, and maize are the prices of "U.S. No. 1 hard red winter, ordinary protein, prompt shipment, FOB $/Mt Gulf of Mexico ports," "Thai, white milled, 5 percent broken, nominal price quotes, FOB Bangkok," and "U.S. No. 2 yellow, prompt shipment, FOB Gulf of Mexico ports." In our CGE analysis, we follow these definitions and examine impacts of various shocks on the export prices of wheat and maize by the US, and that of processed rice by Thailand all in terms of the US dollar.

[8] The productivity is measured by the yield per arable land reported in FAOSTAT.

[9] As Ukraine also set export quotas (World Bank (2008)) but actually carried out more exports, reported by FAOSTAT, than the quota ceiling, we do not consider its export restriction.

3. Simulation Results

The crop failure was the largest contributor to the wheat price rise among the four factors, while it little affected the other markets (Table 5). Although Ukraine was often quoted as one of the major cause of wheat shortage, it did not give any sizable shock to the world export supply (Figure 5). It should also be noted that this price rise was brought about through the contraction of the wheat exports, not through any sizable loss of production (Scenario C). Export restrictions directly cut the wheat exports to raise its price further (Scenario R). On the other hand, the US dollar appreciated due to the petroleum price rise; this led to a moderate rise of the dollar-denominated wheat price (Scenario P).

While no productivity shock occurred in the rice sector, the export restrictions were the major cause of its price rise (Table 5). This price rise is particularly sharp, partly because the international rice market was far thinner than that for other crops and partly because export restrictions covered rice more widely than others. Among several incidences of rice export restrictions, those by Vietnam and India were marked (Figure 5). Although we assume shocks that are anticipated to cause crop price rises, our simulation result shows a fall of the international rice price. Because the petroleum price rise increased the hard currency expenses for oil imports by Thailand and caused a depreciation of the Thai baht, the rice price fell, as measured by the Thai export price in US dollars,.

The maize price was driven mainly by two energy-related factors: the petroleum price rise and the emergence of biofuels (Table 5). The former caused a demand for biofuel production as a substitute of petroleum. The impact of the latter was far larger. Maize was used for the biofuels production in the US and reduced its maize exports to trigger a price rise that was twice as large as that caused by the petroleum price rise.

In sum, the crop failure caused a price rise only in the wheat market. The export restrictions hit the rice market significantly but the others only a little. This result is similar to that of Charlebois' (2008) partial equilibrium analysis. Higher oil prices caused the price rises of wheat and maize to some extent, which were, however, much smaller than the estimates by Yang et al. (2008). This is because while Yang et al. (2008) conduct cumulative simulations for three years, we do one-shot short-run static analysis. Taking account of the realistic farm-land switching, the emergence of biofuels triggered a jump only in the maize price, while Rosegrant (2008) and Yang et al. (2008) suggest much larger impacts on all of these three crops. All the four shocks pushed up the crop prices by 10% or so. However, they can explain only a fraction of the whole price rises in 2008—about 90% of the price hikes should be attributed to non-real-side factors, i.e., speculation, as many earlier studies conclude.[10]

As Wright (2011) argues, the impacts of these shocks tends to be large when the crop stock level is very low, which makes the aggregate crop demand less price-elastic. Although we do not explicitly consider such stock behavior in our CGE model, we assume a smaller elasticity for the crop import demand (more specifically, a smaller elasticity of substitution in the Armington functions) to approximate such a situation. The results with a smaller elasticity, shown in Appendix III as a part of our sensitivity analysis, do not indicate any significant difference in our simulation results. Besides, it should be noted that the elasticity of substitution for the (top-level) Armington function assumed as the central case is 1.3 for maize following the GTAP database. This is indeed low for crops.

4. Conclusion

We reviewed the impacts of crop failures, export restrictions on wheat and rice, the oil price hike, and biofuels emergence and speculation on the world crop prices using a world trade CGE model. Our key finding is that the real-side factors were not the main price driver during the recent commodity boom period, even when we consider the recent wheat crop failures in Australia and Ukraine, the latest evolution of the biofuels emergence, and

[10] This result is robust irrespective of the assumed elasticities for the Armington functions, the food composite function, and the energy composite functions. The results of sensitivity analysis are shown in Appendix III.

the rigidity of farm-land switching. Therefore, conventional policy interventions would not be effective to fight against crop price hikes. That is, even if we prepare buffer stocks for possible lost harvests or temporal export restrictions, we can reduce a price hike by only 5–10%, far smaller than the actual crop price rises. Although many countries have actually kept huge oil reserves, comparable to their domestic use for several months, these reserves did not prevent oil price rises. On the other hand, the new linkage between maize and petroleum markets through biofuels calls for a consistent policy package. While the petroleum price rise disturbed the maize market through increased biofuels production, the subsidized biofuels production further worsened the situation. We should have promoted research and development activities on biofuels production technologies, rather than increasing the production of biofuels, which consumed more maize and exacerbated the crop price hikes.

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Figures and Tables

Table 1: Crop and its Related Market Shocks in 2007/2008

Scenario Factor	Country	Sector	Type of Shock	Magnitude
Crop Failures	Australia	Wheat	Productivity Decline	35%
	Ukraine	Wheat		28%
Export Restrictions	Argentina	What	Export Tax	28%
		Maize		25%
	China	Wheat		20%
		Rice		5%
		Maize		
	Egypt	Rice	Export Ban	95% Export Cut*
	India	Wheat		
		Rice		
	Vietnam	Rice		
	Russia	Wheat	Export Tax	40%
Crude Oil Price Hike	World	Crude Oil	Export Price Rise	126%
Biofuel Productions	Brazil	Bioethanol	Increase of Production	162%
	USA			255%
	EU	Biodiesel		345%

Source: FAOSTAT, Sharma (2011), USDA (2008), and World Bank (2008).

Note: Export ban is approximated with imposition of a 95% export quotas.

Table 2: Estimates of Price Rise Factors

Impacts of	on Price Rises of Wheat [%]	Rice [%]	Maize [%]	Source	Model	Period
Export Restrictions	2	7–16	2–3	Charlebois (2008)	PE	2007, 2008
Petroleum Price Rise	18	–	31	Yang et al. (2008)	CGE	2005–08
	20	–	24	Mitchell (2008)	Cost Analysis	2002–07
Biofuels Production	22	21	39	Rosegrant (2008)	PE	2000–07
	26	–	44	Yang et al. (2008)	CGE	2005–08

Note: PE and CGE refer to partial equilibrium and computable general equilibrium, respectively.

Table 3: Country and Sector Aggregations

Country	Sector
Argentina	Paddy Rice [a]
Australia	Wheat [a]
Brazil	Maize [a]
China	Other Grains [a]
Egypt	Oil Seeds [a]
India	Other Agriculture [a]
Philippines	Sugarcane and Beet [a]
Russia	Processed Rice [a]
Thailand	Other Foods [a]
Ukraine	Coal [b]
USA	Gas [b]
Vietnam	Electricity [b]
EU	Oil [c]
Rest of the World	Bioethanol [c]
	Biodiesel [c]
	Transport
	Others

Note: a, b, and c indicate goods included in the food composite, non-liquid energy goods, and liquid energy goods, respectively.

Table 4: Scenario Table

Scenario	Scenario Factor			
	Crop Failures	Export Restrictions	Petroleum Price Rise	Biofuels Emergence
Base Run	–	–	–	–
C	yes	–	–	–
R	–	yes	–	–
P	–	–	yes	–
B	–	–	–	yes
A	yes	yes	yes	yes

Table 5: Changes of Crop Prices and Decomposition of the Crop Price Hikes

Scenario	Changes [%]			Share of Impact [%]		
	Wheat	Rice	Maize	Wheat	Rice	Maize
Actual Price Rises	87.4	164.5	79.3	100.0	100.0	100.0
C (Crop Failure)						
Price	4.5	0.0	–0.1	5.2	0.0	–0.1
Production	–0.2	0.0	0.0			
Exports	–7.3	0.0	–0.1			
R (Export Restrictions)						
Price	2.0	9.7	0.5	2.2	5.9	0.6
Production	0.0	0.0	0.0			
Exports	–3.5	–30.6	–1.6			
P (Petroleum Price Rise)						
Price	1.8	–1.6	4.5	2.1	–0.9	5.6
Production	0.0	–0.3	4.9			
Exports	–0.9	0.2	1.2			
B (Biofuels Emergence)						
Price	–0.1	–0.1	9.0	–0.1	–0.1	11.4
Production	–0.1	–0.1	7.4			
Exports	–0.1	–0.1	–2.9			
Interactive Effects	0.3	–0.2	–3.0	0.4	–0.1	–3.8
A (All)						
Price	8.6	7.8	10.9	9.8	4.8	13.8
Production	0.0	–0.4	8.1			
Exports	–11.4	–29.6	–2.4			
The Rest (Actual–A)	78.8	156.6	68.4	90.2	95.2	86.2

Note: Price: crop prices of the representative exporters (i.e., the US for wheat and maize and Thailand for rice). Production and exports: the Laspeyres quantity index of world production and exports.

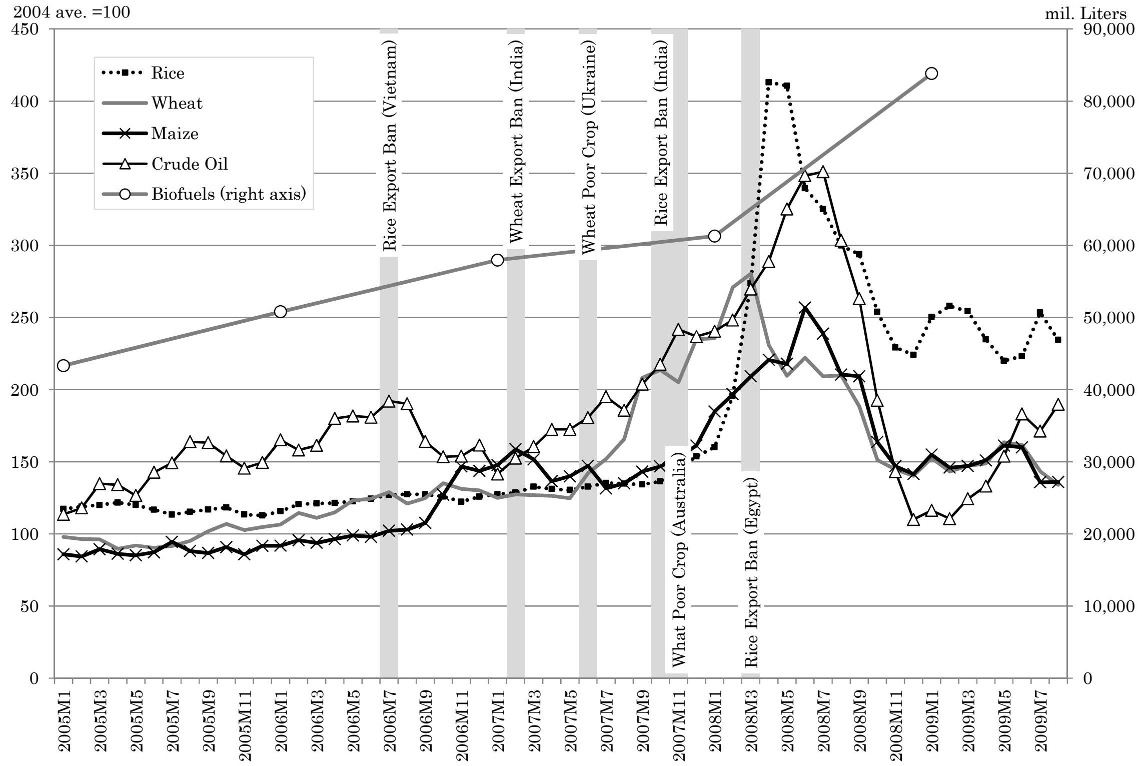


Figure 1: World Nominal Grain Prices and Biofuel Production

Data Source: IMF Primary Commodity Prices, European Biodiesel Board, and Renewable Fuels Association.

Note: 2004 average price of each commodity = 100.

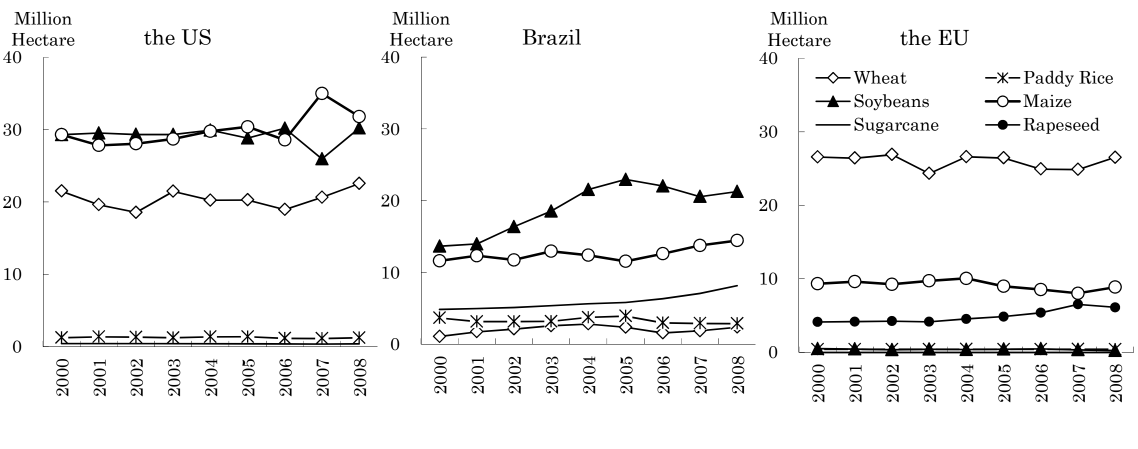


Figure 2: Land Uses in the US, Brazil, and the EU

Data Source: FAOSTAT

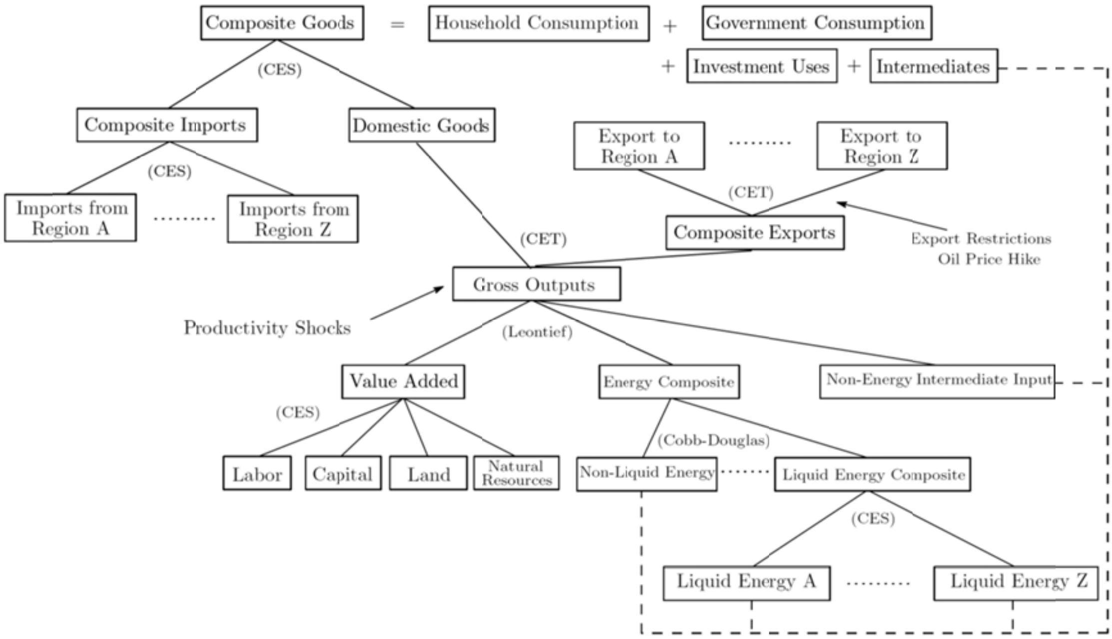


Figure 3: Model Structure

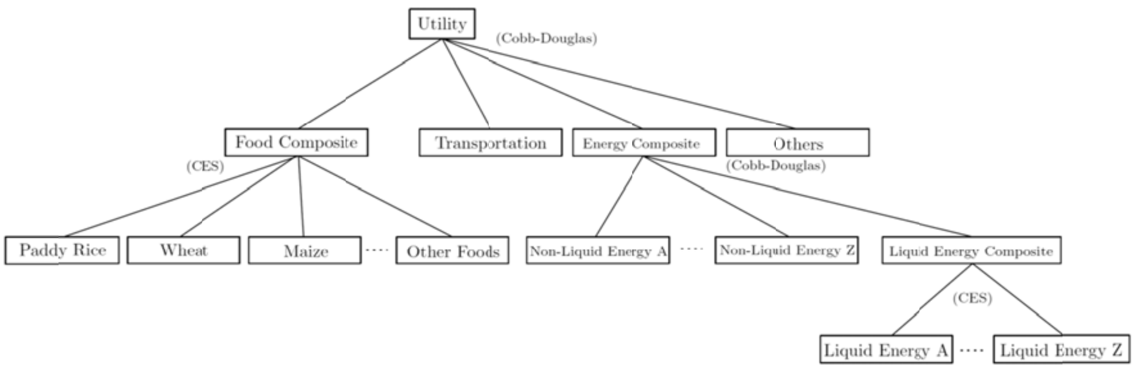


Figure 4: Structure of the Household Consumption

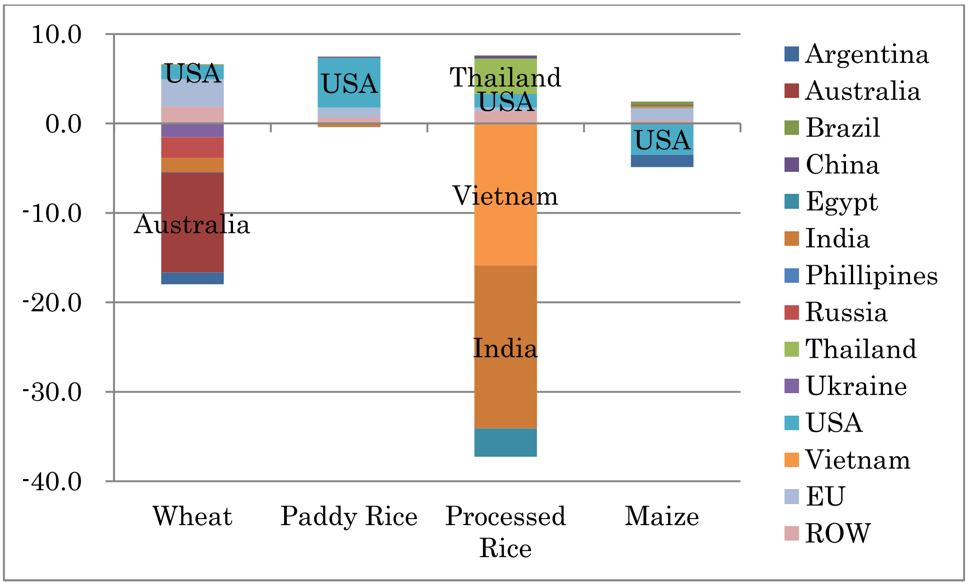
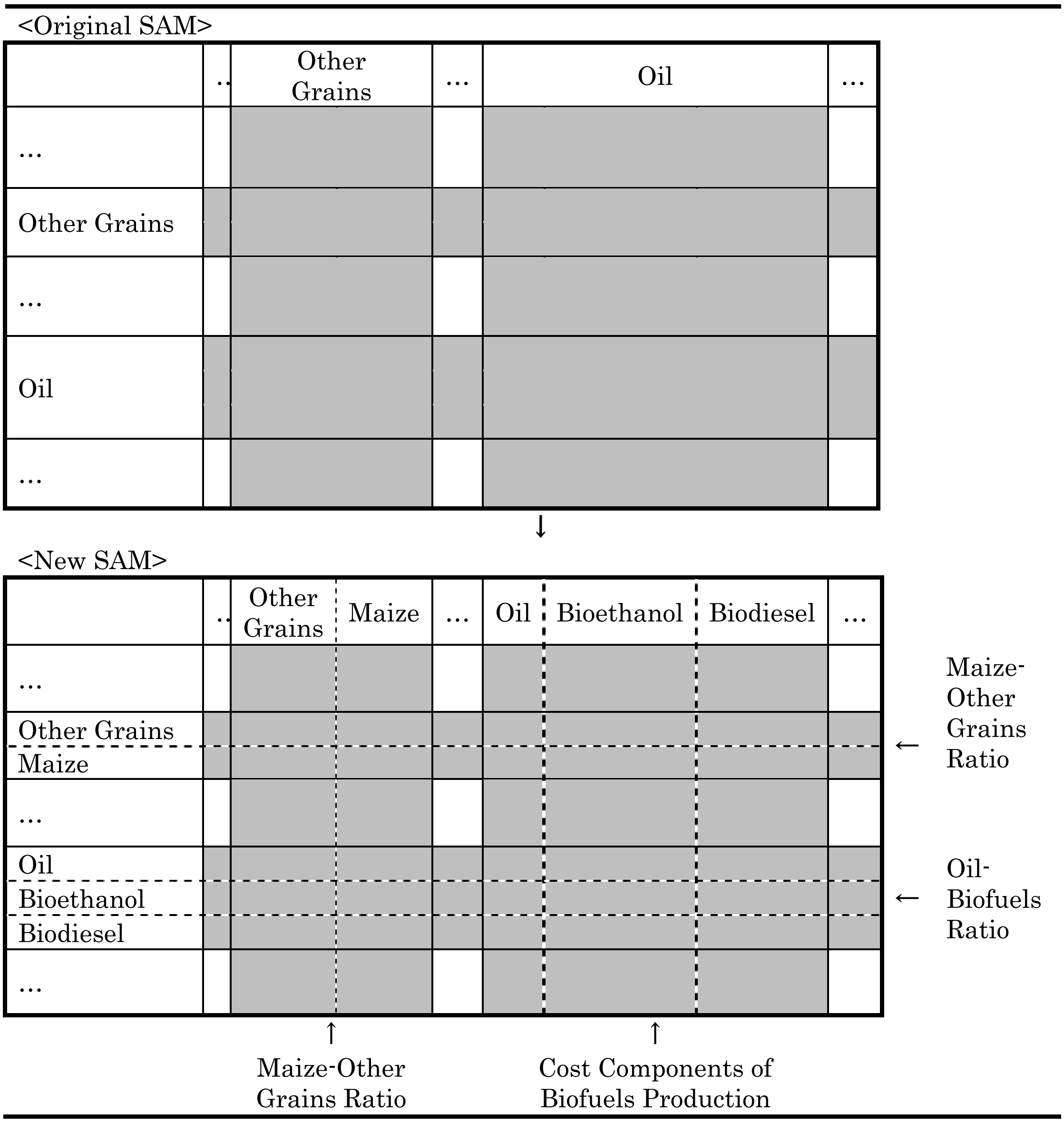


Figure 5: Changes of Exports in Scenario A [unit: %]

Appendix I: Splitting Sectors in the GTAP Database

Maize is not distinguished but included as a part of other grains in the original GTAP database version 7.1; neither bioethanol nor biodiesel is identified there. Therefore, we newly create these three sectors by splitting the other grains and the oil sectors (Table I.1). Considering the relative size of the maize production vis-à-vis the other grains' (i.e., cereals other than rice and wheat) reported in FAOSTAT, we split the row and column of the other grains in the original social accounting matrix (SAM), constructed on the basis of the GTAP database. The column of the original oil sector and biofuels trade are split based on the cost component information and trade flows provided by Taheripour et al. (2008) with the biofuels production and price quoted for 2004 from various sources (Table II). The row of the original oil sector is split considering the share of oil and biofuels consumption. As these new inputs unbalance the SAM, we adjust it by solving a constrained matrix problem, à la Hosoe et al. (2010, Ch. 4).

Table I: Splitting Maize and Biofuels Sectors



Note: Maize-other grains ratio is computed by FAOSTAT. The cost components of biofuels production and biofuels trade are reported by Taheripour et al. (2008). Data sources of other biofuels data are shown in Table II.

Table II: Biofuels Data Sources

Data	Fuel Type	Data Source
Production	Bioethanol	F.O. Licht, World Ethanol & Biofuels Report
	Biodiesel	National Biodiesel Board (the US) http://www.biodiesel.org/pdf_files/fuelfactsheets/Production_Graph_Slide.pdf European Biodiesel Board (the EU) http://www.ebb-eu.org/prev_stats_production.php
Price	Bioethanol & biodiesel	US Department of Energy "The Alternative Fuel Price Report," March 23, 2004. http://www.afdc.energy.gov/afdc/pdfs/afpr_3_23_04.pdf

Appendix II: Model Equations

The full description of our world trade computable general equilibrium model is shown below.

-Symbols

Sets

i, j :	commodities/sectors (other than the food composite)
fd :	food commodities/sectors
nfd :	non-food commodities/sectors
en :	energy commodities (b.+c. in Table 3)
nen :	non-energy commodities (all but b.+c. in Table 3)
nlq:	non-liquid energy commodities (b. in Table 3)
lq:	liquid energy commodities (c. in Table 3)
r, s, r' :	regions
h, k :	factors (capital (CAP), land (LAN), labor (LAB), natural resources (NATRES))
nl :	factors other than labor

Endogenous variables

$X_{i,r}^{p}$:	household consumption
XFD_r :	food composite
ECH_r :	energy composite good for household
LQH_r :	liquid energy composite good for household
$X_{i,j,r}$:	intermediate uses of the i-th good by the j-th sector
$F_{h,j,r}$:	factor uses
$EC_{j,r}$:	energy composite good
$LQ_{j,r}$:	liquid energy composite good
$Y_{j,r}$:	value added
$Z_{j,r}$:	gross output
$Q_{i,r}$:	Armington composite good
$M_{i,r}$:	composite imports
$D_{i,r}$:	domestic goods
$E_{i,r}$:	composite exports
$T_{i,r,s}$:	inter-regional transportation from the r-th region to the s-th region
TT_r :	exports of inter-regional shipping service by the r-th region
Q^{s} :	composite inter-regional shipping service
S_r^{p} :	household savings

S_r^g : government savings
T_r^d : direct taxes
$T_{j,r}^z$: production taxes
$T_{j,s,r}^m$: import tariffs
$T_{j,r,s}^e$: export taxes
$T_{h,j,r}^f$: factor input taxes

p_r^{XFD} : price of food composite
$p_{i,r}^q$: price of Armington composite goods
$p_{h,j,r}^f$: price of factors
$p_{j,r}^{ec}$: price of energy composite good
$p_{j,r}^{lq}$: price of liquid fuel composite good
p_r^{ech} : price of energy composite good for household
p_r^{lqh} : price of liquid fuel for household
$p_{j,r}^y$: price of value added
$p_{i,r}^z$: price of gross output
$p_{i,r}^m$: price of composite imports
$p_{i,r}^d$: price of domestic goods
$p_{i,r}^e$: price of composite exports
$p_{i,r,s}^t$: price of goods shipped from the r-th region to the s-th region
p^s : inter-regional shipping service price in US dollars
$\varepsilon_{r,s}$: exchange rates to convert the r-th region's currency into the s-th region's currency
CPI_r : consumer price index (numeraire)

Exogenous variables

S_r^f : current account deficits in US dollars
$FF_{h,j,r}$: factor endowment initially employed in the j-th sector
$TFP_{j,r}$: productivity of j-th sector
$\overline{X_{i,r}^g}$: government consumption
$\overline{X_{i,r}^v}$: investment uses
$Q_{i,r}^0$: initial Armington composite good
τ_r^d : direct tax rates
$\tau_{i,r}^z$: production tax rates
$\tau_{i,s,r}^m$: import tariff rates on inbound shipping from the s-th region

$\tau^{e}_{i,r,s}$: export tax rates on outbound shipping to the s-th region

$\tau^{s}_{i,r,s}$: inter-regional shipping service requirement per unit transportation of the i-th good from the r-th region to the s-th region

$\tau^{f}_{h,j,r}$: factor input tax rates

-Household

(Utility function: $UU_r = XFD_r^{\alpha_r^{XFD}} \times ECH_r^{\alpha_r^{ECH}} \times \prod_{fd} X^{p\ \ \alpha_{fd,r}}_{fd,r}$ $\quad \forall r$ (B.1)

Consumption demand functions

$$X^{p}_{fd,r} = \frac{\alpha_{fd,r}}{p^{q}_{fd,r}} \left(\sum_{h,j} p^{f}_{h,j,r} F_{h,j,r} - T^{d}_{r} - S^{p}_{r} \right) \qquad \forall fd, r \qquad (B.2)$$

$$XFD_r = \frac{\alpha_r^{XFD}}{p_r^{XFD}} \left(\sum_{h,j} p^{f}_{h,j,r} F_{h,j,r} - T^{d}_{r} - S^{p}_{r} \right) \qquad \forall r \qquad (B.3)$$

$$ECH_r = \frac{\alpha_r^{ECH}}{p_r^{ECH}} \left(\sum_{h,j} p^{f}_{h,j,r} F_{h,j,r} - T^{d}_{r} - S^{p}_{r} \right) \qquad \forall r \qquad (B.4)$$

Food composite aggregation function

$$XFD_r = \Theta_r \left(\sum_{fd} \Delta_{fd,r} X^{p\ \Psi}_{fd,r} \right)^{1/\Psi} \qquad \forall r \qquad (B.5)$$

(Note that $\Psi = (\varepsilon^f - 1)/\varepsilon^f$.)

$$X^{p}_{fd,r} = \left(\frac{\Theta_r^{\ \Psi} \Delta_{fd,r} p_r^{XFD}}{p^{q}_{fd,r}} \right)^{\frac{1}{1-\Psi}} XFD_r \qquad \forall fd, r \qquad (B.6)$$

Energy composite aggregation function for household

$$ECH_r = b_r^{ech} \left(\prod_{nlq} X^{p\ \ \beta^{ECH}_{nlq,r}}_{nlq} \times LQH_r^{\beta_r^{LQHC}} \right) \qquad \forall r \qquad (B.7)$$

$$X^{p}_{nlq,r} = \frac{\beta^{ECH}_{nlq,r}}{p^{q}_{nlq,r}} p_r^{ech} ECH_r \qquad \forall nlq, r \qquad (B.8)$$

$$LQH_r = \frac{\beta_r^{LQHC}}{p_r^{lqh}} p_r^{ech} ECH_r \qquad \forall r \qquad (B.9)$$

Liquid fuel composite aggregation function for household

$$LQH_r = b_r^{LQH} \left(\sum_{lq} \beta^{LQH}_{lq,r} X^{p\ \Xi}_{lq,r} \right)^{1/\Xi} \qquad \forall r \qquad (B.10)$$

(Note that $\Xi = (\sigma^{lqh} - 1)/\sigma^{lqh}$.)

$$X^{p}_{lq,r} = \left(\frac{b_r^{LQH^{\Xi}} \beta^{LQH}_{lq,r} p_r^{lqh}}{p^{q}_{lq,r}} \right)^{\frac{1}{1-\Xi}} LQH_r \qquad \forall lq, r \qquad \text{(B.11)}$$

-Value added producing firm

Factor demand function

$$F_{h,j,r} = \left(\frac{b_{j,r}^{\eta_j^{va}} \beta_{h,j,r} p^{y}_{j,r}}{\left(1+\tau^{f}_{h,j,r}\right) p^{f}_{h,j,r}} \right)^{\frac{1}{1-\eta_j^{va}}} Y_{j,r} \qquad \forall h, j, r \qquad \text{(B.12)}$$

Value added production function

$$Y_{j,r} = b_{j,r} \left(\sum_h \beta_{h,j,r} F_{h,j,r}^{\eta_j^{va}} \right)^{1/\eta_j^{va}} \qquad \forall j, r \qquad \text{(B.13)}$$

Energy composite aggregation function

$$EC_{j,r} = b^{EC}_{j,r} \left(\prod_{nlq} X_{nlq,j,r}^{\beta^{EC\_X}_{nlq,j,r}} \right) \times LQ_{j,r}^{\beta^{EC\_LQ}_{j,r}} \qquad \forall j, r \qquad \text{(B.14)}$$

$$X_{nlq,j,r} = \frac{\beta^{EC\_X}_{nlq,j,r}}{p^{q}_{j,r}} p^{ec}_{j,r} EC_{j,r} \qquad \forall nlq, j, r \qquad \text{(B.15)}$$

$$LQ_{j,r} = \frac{\beta^{EC\_LQ}_{j,r}}{p^{lq}_{j,r}} p^{ec}_{j,r} EC_{j,r} \qquad \forall j, r \qquad \text{(B.16)}$$

Liquid fuel composite aggregation function

$$LQ_{j,r} = b^{LQ}_{j,r} \left(\sum_{lq} \beta^{LQ}_{lq,j,r} X_{lq,j,r}^{\hbar} \right)^{1/\hbar} \qquad \forall j, r \qquad \text{(B.17)}$$

(Note that $\hbar = (\sigma^{lq} - 1)/\sigma^{lq}$.)

$$X_{lq,j,r} = \left(\frac{b_{j,r}^{LQ^{\hbar}} \beta^{LQ}_{lq,j,r} p^{lq}_{j,r}}{p^{q}_{lq,j,r}} \right)^{\frac{1}{1-\hbar}} LQ_{j,r} \qquad \forall lq, j, r \qquad \text{(B.18)}$$

-Gross output producing firm

(Production function: $Z_{j,r} = TFP_{j,r} \min\left(\left\{ \frac{X_{nen,j,r}}{ax_{nen,j,r}} \right\}_i, \frac{Y_{j,r}}{ay_{j,r}}, \frac{EC_{j,r}}{aec_{j,r}} \right)$ $\forall j, r$) (B.19)

Demand function for intermediates

$$X_{nen,j,r} = \frac{ax_{nen,j,r} Z_{j,r}}{TFP_{j,r}} \qquad \forall nen, j, r \qquad \text{(B.20)}$$

Demand function for energy composite goods

$$EC_{j,r} = \frac{aec_{j,r} Z_{j,r}}{TFP_{j,r}} \qquad \forall j,r \qquad \text{(B.21)}$$

Demand function for value added

$$Y_{j,r} = \frac{ay_{j,r} Z_{j,r}}{TFP_{j,r}} \qquad \forall j,r \qquad \text{(B.22)}$$

Unit price function

$$p^z_{j,r} = \frac{1}{TFP_{j,r}} \left(\sum_i ax_{nen,j,r} p^q_{nen,r} + ay_{j,r} p^y_{j,r} + aec_{j,r} p^{ec}_{j,r} \right) \qquad \forall j,r \qquad \text{(B.23)}$$

-Government

Demand function for government consumption

$$p^q_{i,r} \overline{X^g_{i,r}} = \left(T^d_r + \sum_{h,j} T^f_{h,j,r} + \sum_j T^z_{j,r} + \sum_{j,s} T^m_{j,s,r} + \sum_{j,s} T^e_{j,r,s} - S^g_r \right) \qquad \forall i,r \qquad \text{(B.24)}$$

Direct tax revenue

$$T^d_r = \tau^d_r \sum_{h,j} p^f_{h,j,r} F_{h,j,r} \qquad \forall r \qquad \text{(B.25)}$$

Production tax revenue

$$T^z_{j,r} = \tau^z_{j,r} p^z_{j,r} Z_{j,r} \qquad \forall j,r \qquad \text{(B.26)}$$

Import tariff revenue

$$T^m_{j,s,r} = \tau^m_{j,s,r} \left[\left(1 + \tau^e_{j,s,r}\right) \varepsilon_{s,r} p^t_{j,s,r} + \tau^s_{j,s,r} \varepsilon_{USA,r} p^s \right] T_{j,s,r} \qquad \forall j,s,r \qquad \text{(B.27)}$$

Export tax revenue

$$T^e_{j,r,s} = \tau^e_{j,r,s} p^t_{j,r,s} T_{j,r,s} \qquad \forall j,r,s \qquad \text{(B.28)}$$

Factor input tax revenue

$$T^f_{h,j,r} = \tau^f_{h,j,r} p^f_{h,j,r} F_{h,j,r} \qquad \forall h,j,r \qquad \text{(B.29)}$$

-Investment

Demand function for commodities for investment uses

$$p^q_{i,r} \overline{X^v_{i,r}} = \left(S^p_r + S^g_r + \varepsilon_{USA,r} S^f_r \right) \qquad \forall i,r \qquad \text{(B.30)}$$

-Armington composite good producing firm

Composite good production function

$$Q_{i,r} = \gamma_{i,r} \left(\delta^m_{i,r} M_{i,r}{}^{\eta_i} + \delta^d_{i,r} D_{i,r}{}^{\eta_i} \right)^{1/\eta_i} \qquad \forall i,r \qquad \text{(B.31)}$$

Composite import demand function

$$M_{i,r} = \left(\frac{\gamma_{i,r}{}^{\eta_i} \delta^m_{i,r} p^q_{i,r}}{p^m_{i,r}} \right)^{\frac{1}{1-\eta_i}} Q_{i,r} \qquad \forall i,r \qquad \text{(B.32)}$$

Domestic good demand function

$$D_{i,r} = \left(\frac{\gamma_{i,r}{}^{\eta_i} \delta^d_{i,r} p^q_{i,r}}{p^d_{i,r}} \right)^{\frac{1}{1-\eta_i}} Q_{i,r} \qquad \forall i,r \qquad \text{(B.33)}$$

-Import variety aggregation firm

Composite import production function

$$M_{i,r} = \omega_{i,r} \left(\sum_s \kappa_{i,s,r} T_{i,s,r}{}^{\varpi_i} \right)^{1/\varpi_i} \qquad \forall i,r \qquad \text{(B.34)}$$

Import demand function

$$T_{i,s,r} = \left(\frac{\omega_{i,r}{}^{\varpi_i} \kappa_{i,s,r} p^m_{i,r}}{\left(1+\tau^m_{i,s,r}\right)\left[(1+\tau^e_{i,s,r})\varepsilon_{s,r} p^t_{i,s,r} + \tau^s_{i,s,r} \varepsilon_{USA,r} p^s\right]} \right)^{\frac{1}{1-\varpi_i}} M_{i,r} \qquad \forall i,s,r \qquad \text{(B.35)}$$

-Gross output transforming firm

i) For $i = TRS$ (transportation):

$$Z_{i,r} - TT_r = \theta_{i,r} \left(\xi^e_{i,r} E_{i,r}{}^{\phi_i} + \xi^d_{i,r} D_{i,r}{}^{\phi_i} \right)^{1/\phi_i} \qquad \forall i,r \qquad \text{(B.36)}$$

$$E_{i,r} = \left(\frac{\theta_{i,r}{}^{\phi_i} \xi^e_{i,r} \left(1+\tau^z_{i,r}\right) p^z_{i,r}}{p^e_{i,r}} \right)^{\frac{1}{1-\phi_i}} \left(Z_{i,r} - TT_r \right) \qquad \forall i,r \qquad \text{(B.37)}$$

$$D_{i,r} = \left(\frac{\theta_{i,r}{}^{\phi_i} \xi^d_{i,r} \left(1+\tau^z_{i,r}\right) p^z_{i,r}}{p^d_{i,r}} \right)^{\frac{1}{1-\phi_i}} \left(Z_{i,r} - TT_r \right) \qquad \forall i,r \qquad \text{(B.38)}$$

ii) For $i \neq TRS$:

$$Z_{i,r} = \theta_{i,r} \left(\xi^e_{i,r} E_{i,r}{}^{\phi_i} + \xi^d_{i,r} D_{i,r}{}^{\phi_i} \right)^{1/\phi_i} \qquad \forall i,r \qquad \text{(B.39)}$$

$$E_{i,r} = \left(\frac{\theta_{i,r}{}^{\phi_i} \xi^e_{i,r} \left(1+\tau^z_{i,r}\right) p^z_{i,r}}{p^e_{i,r}} \right)^{\frac{1}{1-\phi_i}} Z_{i,r} \qquad \forall i,r \qquad \text{(B.40)}$$

$$D_{i,r} = \left(\frac{\theta_{i,r}{}^{\phi_i} \xi^d_{i,r} \left(1+\tau^z_{i,r}\right) p^z_{i,r}}{p^d_{i,r}} \right)^{\frac{1}{1-\phi_i}} Z_{i,r} \qquad \forall i,r \qquad \text{(B.41)}$$

Balance of Payments

$$\begin{aligned} &\sum_{i,s} (1+\tau^e_{i,r,s}) \varepsilon_{r,USA} p^{qt}_{i,r,s} QT_{i,r,s} + S^f_r + SVC^0_r + \varepsilon_{r,USA} (1+\tau^z_{TRS,r}) p^z_{TRS,r} QTS_r \\ &= \sum_{i,s} \left[\tau^s_{i,s,r} p^{qqt} \varepsilon_{USA,USA} + (1+\tau^e_{i,s,r}) p^{qt}_{i,s,r} \varepsilon_{s,USA} \right] QT_{i,s,r} \end{aligned} \qquad \forall r \qquad \text{(B.42)}$$

-Export variety producing firm

Composite export transformation function

$$E_{i,r} = \varsigma_{i,r} \left(\sum_s \rho_{i,r,s} T_{i,r,s}{}^{\varphi_i} \right)^{1/\varphi_i} \qquad \forall i,r \qquad \text{(B.43)}$$

Export supply function

$$T_{i,r,s} = \left(\frac{\varsigma_{i,r}{}^{\varphi_i} \rho_{i,r,s} p^e_{i,r}}{(1+\tau^e_{i,r,s}) p^t_{i,r,s}} \right)^{\frac{1}{1-\varphi_i}} E_{i,r} \qquad \forall i,r,s \qquad \text{(B.44)}$$

-Inter-regional shipping sector

Inter-regional shipping service production function

$$Q^s = c \prod_r TT_r^{\chi_r} \qquad \text{(B.45)}$$

Input demand function for international shipping service provided by the r-th country

$$TT_r = \frac{\chi_r}{\left(1+\tau^z_{TRS,r}\right) \varepsilon_{r,USA} p^z_{TRS,r}} p^s Q^s \qquad \forall r \qquad \text{(B.46)}$$

-Market-clearing conditions

Commodity market

$$Q_{i,r} = X^p_{i,r} + \overline{X^g_{i,r}} + \overline{X^v_{i,r}} + \sum_j X_{i,j,r} \qquad \forall i,r \qquad \text{(B.47)}$$

Factor markets other than labor

$$FF_{nl,j,r} = F_{nl,j,r} \qquad \forall nl,j,r \qquad \text{(B.48)}$$

Labor market

$$\sum_j FF_{LAB,j,r} = \sum_j F_{LAB,j,r} \qquad \forall r \qquad \text{(B.49)}$$

$$p^f_{LAB,j,r} = p^f_{LAB,i,r} \qquad \forall i,j,r \qquad \text{(B.50)}$$

Foreign exchange rate arbitrage condition

$$\varepsilon_{r,r'} \cdot \varepsilon_{r',s} = \varepsilon_{r,s} \qquad \forall r,r',s \qquad \text{(B.51)}$$

Inter-regional shipping service market

$$Q^s = \sum_{i,r,s} \tau^s_{i,r,s} T_{i,r,s} \qquad \text{(B.52)}$$

Consumer price index (numeraire)

$$CPI_r = \sum_i \frac{Q_{i,r}}{Q^0_{i,r}} p^q_{i,r} \qquad \forall r \qquad \text{(B.53)}$$

Appendix III: Sensitivity Analysis

As in many CGE analyses, our simulation results depend more or less on various parameters in the model that we assume. We conduct sensitivity analysis with respect to such key parameters as the Armington (1969) elasticity, the elasticity of substitution among various energy inputs, the one among foods, and the one among primary factor input. We also simulate the same shocks but assume perfect mobility of primary factors among sectors as Yang et al. (2008) assumed.

When we assume a larger elasticity value for the Armington elasticity, the impacts of the real-side factors are generally found to be larger, but this can explain only a small part of the crop price hikes (Tables II.1–II.2). A smaller elasticity of substitution among primary factors tends to generate a larger impact, particularly in the maize price–the real-side factors account for over 30% of the maize price rise (Tables II.3–II.4). The elasticity of substitution among energy inputs as well as the one among foods affects the simulation results only a little (Tables II.5–II.7). When we assume all the primary factors are mobile among sectors, the economies can adjust to shocks more flexibly. Therefore, the price changes induced by the real-side factors tend to be smaller (Table II.8). Overall, the assumptions about the elasticity parameters and the mobility of primary factors do not significantly alter our simulation results either qualitatively or quantitatively.

Table II.1: Decomposition of Crop Price Hikes (Armington elasticity –30%)

Scenario	Change in Price [%]			Share of Impact [%]		
	Wheat	Rice	Maize	Wheat	Rice	Maize
Impact of						
C (Crop Failure)	4.5	0.0	–0.1	5.2	0.0	–0.1
R (Export Restrictions)	1.9	8.0	0.6	2.2	4.9	0.7
P (Petroleum Price Rise)	1.5	–1.5	5.1	1.7	–0.9	6.5
B (Biofuels Emergence)	–0.1	–0.1	9.9	–0.1	0.0	12.5
Interactive Effects	0.3	–0.2	–4.2	0.3	–0.1	–5.3
A (All)	8.1	6.1	11.3	9.3	3.7	14.3
The Rest (Actual–A)	79.2	158.4	68.0	90.7	96.3	85.7

Table II.2: Decomposition of Crop Price Hikes (Armington elasticity +30%)

Scenario	Change in Price [%]			Share of Impact [%]		
	Wheat	Rice	Maize	Wheat	Rice	Maize
Impact of						
C (Crop Failure)	4.5	–0.1	–0.1	5.2	0.0	–0.1
R (Export Restrictions)	2.0	13.2	0.4	2.3	8.0	0.5
P (Petroleum Price Rise)	2.3	–1.5	3.3	2.7	–0.9	4.1
B (Biofuels Emergence)	–0.1	–0.1	6.8	–0.1	–0.1	8.6
Interactive Effects	0.5	–0.1	–1.0	0.6	0.0	–1.3
A (All)	9.3	11.5	9.4	10.6	7.0	11.9
The Rest (Actual–A)	78.1	152.9	69.9	89.4	93.0	88.1

Table II.3: Decomposition of Crop Price Hikes (elasticity of substitution among primary factors –30%)

Scenario	Change in Price [%]			Share of Impact [%]		
	Wheat	Rice	Maize	Wheat	Rice	Maize
Impact of						
C (Crop Failure)	5.8	–0.1	–0.1	6.6	0.0	–0.1
R (Export Restrictions)	2.4	11.3	0.5	2.7	6.9	0.6
P (Petroleum Price Rise)	1.8	–1.3	8.4	2.1	–0.8	10.6
B (Biofuels Emergence)	–0.2	–0.2	23.2	–0.2	–0.1	29.2
Interactive Effects	0.5	–0.2	–7.2	0.6	–0.1	–9.1
A (All)	10.3	9.6	24.8	11.8	5.8	31.3
The Rest (Actual–A)	77.0	154.9	54.5	88.2	94.2	68.7

Table II.4: Decomposition of Crop Price Hikes (elasticity of substitution among primary factors +30%)

Scenario	Change in Price [%]			Share of Impact [%]		
	Wheat	Rice	Maize	Wheat	Rice	Maize
Impact of						
C (Crop Failure)	3.8	0.0	0.0	4.4	0.0	0.0
R (Export Restrictions)	1.7	8.7	0.5	2.0	5.3	0.7
P (Petroleum Price Rise)	1.8	–1.7	2.4	2.1	–1.1	3.1
B (Biofuels Emergence)	–0.1	–0.1	3.3	–0.1	0.0	4.1
Interactive Effects	0.2	–0.2	–0.9	0.3	–0.1	–1.1
A (All)	7.5	6.7	5.3	8.6	4.1	6.7
The Rest (Actual–A)	79.8	157.8	74.0	91.4	95.9	93.3

Table II.5: Decomposition of Crop Price Hikes (elasticity of substitution among energy inputs –30%)

Scenario	Change in Price [%]			Share of Impact [%]		
	Wheat	Rice	Maize	Wheat	Rice	Maize
Impact of						
C (Crop Failure)	4.5	0.0	–0.1	5.2	0.0	–0.1
R (Export Restrictions)	2.0	9.7	0.5	2.2	5.9	0.6
P (Petroleum Price Rise)	2.0	–1.2	3.4	2.3	–0.7	4.2
B (Biofuels Emergence)	–0.1	–0.1	9.0	–0.1	–0.1	11.3
Interactive Effects	0.4	–0.1	–1.7	0.4	–0.1	–2.1
A (All)	8.8	8.3	11.2	10.1	5.0	14.1
The Rest (Actual–A)	78.5	156.2	68.2	89.9	95.0	85.9

Table II.6: Decomposition of Crop Price Hikes (elasticity of substitution among energy inputs +30%)

Scenario	Change in Price [%]			Share of Impact [%]		
	Wheat	Rice	Maize	Wheat	Rice	Maize
Impact of						
C (Crop Failure)	4.5	0.0	–0.1	5.2	0.0	–0.1
R (Export Restrictions)	2.0	9.7	0.5	2.2	5.9	0.6
P (Petroleum Price Rise)	1.6	–1.9	5.9	1.8	–1.1	7.4
B (Biofuels Emergence)	–0.1	–0.1	9.0	–0.1	–0.1	11.4
Interactive Effects	0.3	–0.3	–4.6	0.4	–0.2	–5.8
A (All)	8.3	7.5	10.7	9.5	4.5	13.5
The Rest (Actual–A)	79.0	157.0	68.6	90.5	95.5	86.5

Table II.7: Decomposition of Crop Price Hikes (elasticity of substitution among foods=1.0)

Scenario	Change in Price [%]			Share of Impact [%]		
	Wheat	Rice	Maize	Wheat	Rice	Maize
Impact of						
C (Crop Failure)	3.9	0.0	0.0	4.5	0.0	0.0
R (Export Restrictions)	1.8	7.4	0.5	2.1	4.5	0.6
P (Petroleum Price Rise)	1.7	–1.2	3.9	2.0	–0.7	4.9
B (Biofuels Emergence)	–0.1	0.0	7.7	–0.1	0.0	9.7
Interactive Effects	0.2	–0.2	–2.6	0.3	–0.1	–3.3
A (All)	7.6	5.9	9.4	8.8	3.6	11.9
The Rest (Actual–A)	79.7	158.6	69.9	91.2	96.4	88.1

Table II.8: Decomposition of Crop Price Hikes (all the primary factors mobile among sectors)

Scenario	Change in Price [%]			Share of Impact [%]		
	Wheat	Rice	Maize	Wheat	Rice	Maize
Impact of						
C (Crop Failure)	0.9	0.0	0.2	1.0	0.0	0.3
R (Export Restrictions)	0.5	4.7	0.7	0.5	2.9	0.9
P (Petroleum Price Rise)	2.6	–4.1	–2.6	2.9	–2.5	–3.2
B (Biofuels Emergence)	1.0	0.1	–6.9	1.2	0.0	–8.7
Interactive Effects	–0.4	–0.4	3.8	–0.5	–0.2	4.8
A (All)	4.5	0.3	–4.8	5.2	0.2	–6.0
The Rest (Actual–A)	82.8	164.2	84.1	94.8	99.8	106.0