Multicommodity International Agricultural Trade Network Equilibrium: Competition for Limited Production and Transportation Capacity Under Disaster Scenarios with Implications for Food Security

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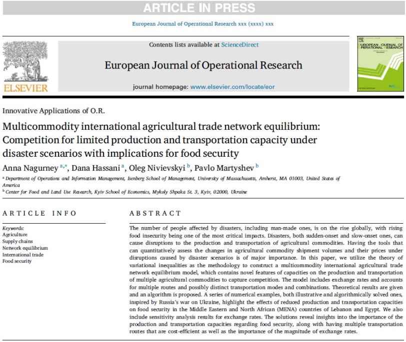

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Innovative Applications of O.R.

Multicommodity international agricultural trade network equilibrium: Competition for limited production and transportation capacity under disaster scenarios with implications for food security

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ABSTRACT

The number of people affected by disasters, including man-made ones, is on the rise globally, with rising food insecurity being one of the most critical impacts. Disasters, both sudden-onset and slow-onset ones, can cause disruptions to the production and transportation of agricultural commodities. Having the tools that can quantitatively assess the changes in agricultural commodity shipment volumes and their prices under disruptions caused by disaster scenarios is of major importance. In this paper, we utilize the theory of variational inequalities as the methodology to construct a multicommodity international agricultural trade network equilibrium model, which contains novel features of capacities on the production and transportation of multiple agricultural commodities to capture competition. The model includes exchange rates and accounts for multiple routes and possibly distinct transportation modes and combinations. Theoretical results are given and an algorithm is proposed. A series of numerical examples, both illustrative and algorithmically solved ones, inspired by Russia's war on Ukraine, highlight the effects of reduced production and transportation capacities on food security in the Middle Eastern and North African (MENA) countries of Lebanon and Egypt. We also include sensitivity analysis results for exchange rates. The solutions reveal insights into the importance of the production and transportation capacities regarding food security, along with having multiple transportation routes that are cost-efficient as well as the importance of the magnitude of exchange rates.

Acknowledgment and Dedication

The authors acknowledge the partnership established between the University of Massachusetts Amherst and the Kyiv School of Economics, which supported this collaboration.

This presentation is dedicated to all Ukrainian farmers who have strived for global food security, even as the full-scale invasion continues.

International agricultural trade provides us with essential agri-food commodities throughout the year, ensuring our food security and simultaneously benefiting the farmers.

International Agricultural Trade and Disasters

- **Our planet and people are being faced with immense challenges brought about by disasters, including man-made ones**.
- **Disasters can have an immense impact on nations, regions, businesses, organizations, and individuals. A multiplicity of disasters can also impact food security**.

Disasters and Food Security

- **Climate change and COVID-19 impacted the affordability and accessibility of agri-food products around the globe**.
- **With the added disruptions of Russia's full-scale invasion of Ukraine, around 47 million people are estimated to have been added to the more than 276 million who were already facing food insecurity**.


Disasters and Food Security

- **The FAO of the United Nations reports that between 20 and 30 percent of the Ukrainian land previously used for cultivating winter crops will probably remain unsown due to the ongoing war**.
- **In addition, there have been immense challenges in getting the exports of agricultural products out of Ukraine with the blockade of the Black Sea in wartime and various bottlenecks**.

Disasters and Food Security

- **With the major earthquake and aftershock striking Turkey and Syria in February 2023, the FAO is assessing their effects on the agricultural sector in both countries**.
- **In Turkey, the early estimate is approximately a 1% decrease in its GDP due to the damages to the agricultural sector**.
- **More than 4 million people in northern parts of Syria have already been identified as being food insecure**.

Disasters and Food Security

- **The Horn of Africa is now experiencing its worst drought recorded in modern history. The ongoing dry spell has caused food insecurity for 21 million people in the region.**
- **From July to December 2022, the number of children facing severe food insecurity in the Horn of Africa region doubled from 10 million to more than 20 million.**
- **The high food prices caused by COVID-19, climate change, and the shortage of grains due to the ongoing war in Ukraine have further complicated the disastrous situation in the region.**

Literature Review

• The intellectual foundations of our work lie in the contributions of Samuelson (1952) and Takayama and Judge (1964, 1971) to spatial price equilibrium (SPE) modeling.

• SPE models have had wide application to the trade of different agricultural products (see, e.g., Thompson (1989), Bishop, Pratt, and Novakovic (1994), Ruijs et al. (2001), Barraza De La Cruz, Pizzolato, and Barraza de La Cruz (2010)).

• They have also gathered attention in the context of the quantification of the impacts of various policies such as quotas (e.g., Nagurney, Li, and Nagurney (2014), Nagurney (2022b), Nagurney, Salarpour, and Dong (2022)), tariffs, including tariff-rate quotas (see, for example, Nagurney, Besik, and Dong (2019)) and ad valorem tariffs (see Nagurney, Nicholson, and Bishop (1996)), as well as non-tariff measures in the form of sanitary and phytosanitary measures (Lopez, Rau, and Woltjer (2019) and Nagurney and Besedina (2023)).

• The inclusion of exchange rates in spatial price equilibrium models is very limited (see Devadoss and Sabala (2020), Nagurney et al. (2023), and Nagurney and Besedina (2023)).

Our Contributions

- **We use the theory of variational inequalities to construct a multicommodity international agricultural trade model, which contains novel features of capacities on the production outputs and on the transportation flows of agricultural commodities.**
- **Our model includes exchange rates, multiple agricultural commodities, multiple possible routes between country supply and demand market pairs, and expanded network equilibrium conditions to include the production and transportation bounds.**
- **The network equilibrium model allows for supply price, demand price, and unit transportation cost functions to depend on the commodity flow variables, and these functions can be nonlinear and asymmetric.**
- **The capacity constraints, along with the generality of the underlying functions, enable the modeling of competition for production and transportation capacity among the commodities.**

The Multicommodity International Agricultural Trade Model

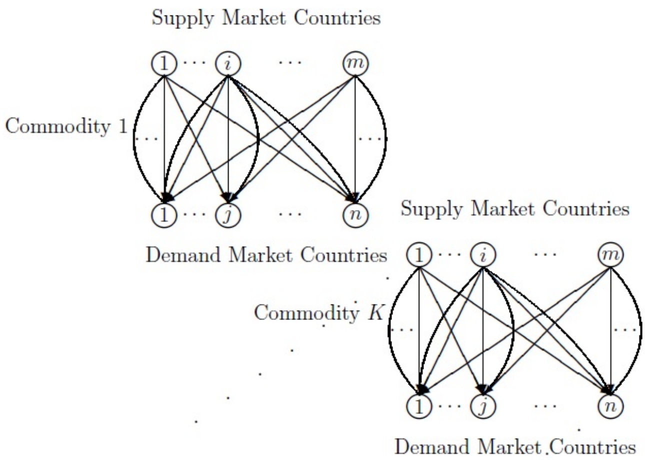


Figure: The Multicommodity International Trade Network

Variables

• Let Q_{ij}^{kl} denote the amount of commodity k produced at country supply market i and shipped on route l to country demand market j. The commodity flows are grouped into the vector $Q \in R_+^{KLmn}$. Associated with each pair of country supply and demand markets (i, j) is an exchange rate e_{ij} for $i = 1, \ldots, m$; $j = 1, \ldots, n$.

• Let s_i^k denote the supply of commodity k produced at country supply market i. All the commodity supplies are grouped into the vector $s \in R_+^{Km}$.

• The demand for commodity k at country demand market j is denoted by d_j^k, and all the demands are gathered into the vector $d \in R_+^{Kn}$.

A trade route can entail transportation via different modes, such as rail, truck, air, or water (sea, river, etc.).

Constraints

The conservation of flow equations are:

$$s_i^k = \sum_{j=1}^{n} \sum_{l=1}^{L} Q_{ij}^{kl}, \quad k = 1, \ldots, K; i = 1, \ldots, m, \tag{1}$$

$$d_j^k = \sum_{i=1}^{m} \sum_{l=1}^{L} Q_{ij}^{kl}, \quad k = 1, \ldots, K; j = 1, \ldots, n. \tag{2}$$

Also, all the commodity shipments must be nonnegative; that is:

$$Q_{ij}^{kl} \geq 0, \quad k = 1, \ldots, K; l = 1, \ldots, L; i = 1, \ldots, m; j = 1, \ldots, n. \tag{3}$$

Transportation Capacity Constraints

Let $\bar{Q}^l_{ij}$ denote the transportation capacity of route l between country supply market i and country demand market j, for all l, i, j. Typically, the units of flow for the agricultural commodities are in tons.

Hence, the following transportation capacity constraints must be satisfied:

$$\sum_{k=1}^{K} Q^{kl}_{ij} \leq \bar{Q}^l_{ij}, \quad l = 1, \ldots, L; i = 1, \ldots, m; j = 1, \ldots, n. \tag{4}$$

Expressions in (4) allow us to capture competition among the commodities for transportation services along particular routes.

Production Capacity Constraints

Let $\bar{S}_i$ denote the production capacity of country supply market i across all the commodities. The below production capacity constraints must be met:

$$\sum_{k=1}^{K} s_i^k \leq \bar{S}_i, \quad i = 1, \ldots, m. \tag{5a}$$

Due to the conservation of flow equations (1), constraints (5a) can take the form:

$$\sum_{k=1}^{K} \sum_{l=1}^{L} \sum_{j=1}^{n} Q_{ij}^{kl} \leq \bar{S}_i, \quad i = 1, \ldots, m. \tag{5b}$$

According to (5a) or (5b), a country supply market i cannot violate its aggregate production capacity.

Lagrange Multipliers

We introduce Lagrange multipliers:

$$\lambda_{ij}^{l}, \quad l = 1, \ldots, L; i = 1, \ldots, m; j = 1, \ldots, n;$$

and:

$$\mu_i, \quad i = 1, \ldots, m;$$

associated with the capacity constraints in (4) and (5b), respectively, and we group these Lagrange multipliers into the vectors $\lambda \in R_+^{Lmn}$ and $\mu \in R_+^m$.

Supply Price Functions

The country supply price functions π_i^k, for all k, i, are:

$$\pi_i^k = \pi_i^k(s), \quad k = 1, \ldots, K; i = 1, \ldots, m. \tag{6a}$$

Due to the conservation of flow equations (1), we may construct country supply price functions $\tilde{\pi}_i^k$, for all k, i, such that:

$$\tilde{\pi}_i^k(Q) \equiv \pi_i^k(s), \quad k = 1, \ldots, K; i = 1, \ldots, m. \tag{6b}$$

Demand Price Functions

The demand price of a commodity k in country j, ρ_j^k, in turn, can depend on the entire vector of demands of the commodities in all countries:

$$\rho_j^k = \rho_j^k(d), \quad k = 1, \ldots, K; j = 1, \ldots, n. \tag{7a}$$

Similarly, due to (2), we may construct new country demand price functions $\tilde{\rho}_j^k$, for all k, j, such that:

$$\tilde{\rho}_j^k(Q) \equiv \rho_j^k(d), \quad k = 1, \ldots, K; j = 1, \ldots, n. \tag{7b}$$

Transportation Cost Functions

The unit transportation cost associated with transporting commodity k from country i to country j on transportation route l is denoted by c_{ij}^{kl} and is as follows:

$$c_{ij}^{kl} = c_{ij}^{kl}(Q), \quad k = 1, \dots, K; l = 1, \dots, L; i = 1, \dots, m; j = 1, \dots, n. \quad (8)$$

The generality of the above transportation cost functions, where the unit transportation cost can depend on the vector of commodity shipments between all pairs of country supply and demand markets, allows one to further capture competition for transportation services among commodities.

Equilibrium Conditions

Definition 1: The Multicommodity International Agricultural Trade Equilibrium Conditions

A multicommodity shipment and Lagrange multiplier pattern $(Q^*, \lambda^*, \mu^*) \in \mathcal{K}^1$, *where* $\mathcal{K}^1 \equiv \{(Q, \lambda, \mu) | (Q, \lambda, \mu) \in R_+^{KLmn+Lmn+m}\}$ *is a multicommodity international agricultural trade network equilibrium with exchange rates, under limited production and transportation capacities, if the following conditions hold: For all commodities* k*;* $k = 1, \ldots, K$*; for all routes* l*;* $l = 1, \ldots, L$*, and for all country supply and demand market pairs:* (i, j)*;* $i = 1, \ldots, m$*;* $j = 1, \ldots, n$*:*

$$(\tilde{\pi}_i^k(Q^*) + c_{ij}^{kl}(Q^*))e_{ij} + \lambda_{ij}^{l*} + \mu_i^* \begin{cases} = \tilde{\rho}_j^k(Q^*), & \text{if } Q_{ij}^{kl*} > 0, \\ \geq \tilde{\rho}_j^k(Q^*), & \text{if } Q_{ij}^{kl*} = 0, \end{cases} \tag{9}$$

Equilibrium Conditions

Definition 1: The Multicommodity International Agricultural Trade Equilibrium Conditions

and for all routes l; $l = 1, \ldots, L$, and all country market pairs (i, j); $i = 1, \ldots, m$; $j = 1, \ldots, n$:

$$\lambda_{ij}^{l*} \begin{cases} \geq 0, & \textit{if } \sum_{k=1}^{K} Q_{ij}^{kl*} = \bar{Q}_{ij}^{l}, \\ = 0, & \textit{if } \sum_{k=1}^{K} Q_{ij}^{kl*} < \bar{Q}_{ij}^{l}, \end{cases} \tag{10}$$

and for all country supply markets i; $i = 1, \ldots, m$:

$$\mu_{i}^{*} \begin{cases} \geq 0, & \textit{if } \sum_{k=1}^{K} \sum_{l=1}^{L} \sum_{j=1}^{n} Q_{ij}^{kl*} = \bar{S}_{i}, \\ = 0, & \textit{if } \sum_{k=1}^{K} \sum_{l=1}^{L} \sum_{j=1}^{n} Q_{ij}^{kl*} < \bar{S}_{i}. \end{cases} \tag{11}$$

Variational Inequality Formulation

Theorem 1: Variational Inequality Formulation of the Multicommodity International Agricultural Trade Equilibrium Conditions

A multicommodity shipment and Lagrange multipliers pattern $(Q^*, \lambda^*, \mu^*) \in \mathcal{K}^1$ *is a multicommodity international agricultural trade network equilibrium with exchange rates, under limited production and transportation capacities, according to Definition 1, if and only if it satisfies the variational inequality:*

$$\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{i=1}^{m}\sum_{j=1}^{n}\Big[(\tilde{\pi}_i^k(Q^*) + c_{ij}^{kl}(Q^*))e_{ij} + \lambda_{ij}^{l*} + \mu_i^* - \tilde{\rho}_j^k(Q^*)\Big] \times (Q_{ij}^{kl} - Q_{ij}^{kl*})$$

$$+\sum_{l=1}^{L}\sum_{i=1}^{m}\sum_{j=1}^{n}\Big[\bar{Q}_{ij}^l - \sum_{k=1}^{K} Q_{ij}^{kl*}\Big] \times (\lambda_{ij}^l - \lambda_{ij}^{l*})$$

$$+\sum_{i=1}^{m}\Big[\bar{S}_i - \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{j=1}^{n} Q_{ij}^{kl*}\Big] \times (\mu_i - \mu_i^*) \geq 0, \quad \forall (Q, \lambda, \mu) \in \mathcal{K}^1. \qquad (12)$$

Variational Inequality Formulation

Standard Form

Variational inequality (12) is now put into standard form (cf. Nagurney (1999)), VI$(F, \mathcal{K})$, where one seeks to determine a vector $X^* \in \mathcal{K} \subset R^{\mathcal{N}}$, such that

$$\langle F(X^*), X - X^* \rangle \geq 0, \quad \forall X \in \mathcal{K}, \tag{13}$$

with F being a given continuous function from $\mathcal{K}$ to $R^{\mathcal{N}}$, where $\mathcal{K}$ is a given closed, convex set, and $\langle \cdot, \cdot \rangle$ denotes the inner product in $\mathcal{N}$-dimensional Euclidean space.

Specifically, we define $X \equiv (Q, \lambda, \mu)$, $\mathcal{K} \equiv \mathcal{K}^1$, and $\mathcal{N} \equiv KLmn + Lmn + m$. Additionally, $F(X) \equiv (F_1(X), F_2(X), F_3(X))$ where $F_1(X)$ consists of the elements: $\left[(\tilde{\pi}_i^k(Q) + c_{ij}^{kl}(Q))e_{ij}) + \lambda_{ij}^l + \mu_i - \tilde{\rho}_j^k(Q)\right], \forall k, l, i, j$, and the components of $F_2(X)$ are: $\left[\bar{Q}_{ij}^l - \sum_{k=1}^K Q_{ij}^{kl}\right], \forall l, i, j$, and $F_3(X)$ is comprised of the elements: $\left[\bar{S}_i - \sum_{k=1}^K \sum_{l=1}^L \sum_{j=1}^n Q_{ij}^{kl}\right], \forall i$.

Clearly, variational inequality (12) can be put into standard form (13).

Numerical Examples

The examples focus on commodity flows from Ukraine to Lebanon and Egypt. The Modified Projection Method (Korpelevich (1977)) is the algorithm used to solve these examples.

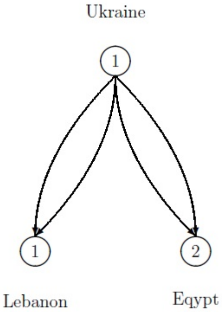


Figure: The International Trade Network for the Examples

Example 1: Pre-War Scenario

This example considers the pre-war scenario when almost all of the grains in Ukraine were exported through their Black Sea ports. There are two commodities: wheat and corn, denoted by $k = 1, 2$, respectively.

The modified projection method yields the following equilibrium commodity shipment pattern:

$$Q_{11}^{11*} = 477,085.5938, \;\; Q_{12}^{11*} = 1,605,672.5000, \;\; Q_{11}^{12*} = 0.0000, \;\; Q_{12}^{12*} = 0.0000,$$

$$Q_{11}^{21*} = 79,128.0781, \quad Q_{12}^{21*} = 560,130.3750, \quad Q_{11}^{22*} = 0.0000, \quad Q_{12}^{22*} = 0.0000.$$

Lebanon imports more than 70% of its wheat and about 20% of its corn from Ukraine, while these percentages for Egypt are 25%, and 5%, for wheat and corn, respectively. Ukraine's wheat exports to Lebanon were at 520,000 tons in 2021. Note that only the maritime routes have positive commodity flows.

Example 1: Pre-War Scenario

The equilibrium commodity supplies and demand are:

$$s_1^{1*} = 2,082,758.1250, \quad s_1^{2*} = 639,258.4375.$$

$$d_1^{1*} = 477,085.5938, \quad d_1^{2*} = 79,128.0781,$$

$$d_2^{1*} = 1,605,672.5000, \quad d_2^{2*} = 560,130.3750.$$

The incurred supply and demand prices in Ukraine in hryvnia at the equilibrium are:

$$\pi_1^1(s^*) = 7,328.3252 = \$266.8542, \quad \pi_1^2(s^*) = 6,971.0166 = \$253.8432.$$

Pre-war, Ukrainian farmers could earn close to \$270 per ton for wheat and corn.

$$\rho_1^1(d^*) = 530,781.1875 = \$351.0457, \quad \rho_1^2(d^*) = 520,752.9063 = \$344.4132,$$

$$\rho_2^1(d^*) = 5,527.3057 = \$351.3862, \quad \rho_2^2(d^*) = 5,555.4214 = \$353.1736.$$

All the Lagrange multipliers were equal to: 0.0000.

Example 2: Early Period Post-Full-Scale Invasion of February 24, 2022

We now consider the early period after the full-scale invasion but before the Black Sea Grain Initiative. During this period, the Black Sea routes were mined and blockaded.

The modified projection method yields the following equilibrium commodity shipment pattern:

$$Q_{11}^{12*} = 216,433.1406, \quad Q_{12}^{12*} = 500,000.0000,$$

$$Q_{11}^{22*} = 0.0000, \quad Q_{12}^{22*} = 0.0000.$$

With the cheaper maritime routes blockaded, the more expensive alternative routes are in use. After the start of the war, the transportation cost of grains inside Ukraine reached an unprecedented level of around $200. The alternative routes are used for the export of wheat but not for corn. Lebanon and Egypt rely heavily on wheat as their main source of nutrition.

Example 2: Early Period Post-Full-Scale Invasion of February 24, 2022

The equilibrium commodity supplies and demands are:

$$s_1^{1*} = 716,432.1875, \quad s_1^{2*} = 0.0000.$$

$$d_1^{1*} = 216,433.1406, \quad d_1^{2*} = 0.0000,$$

$$d_2^{1*} = 500,000.0000, \quad d_2^{2*} = 0.0000.$$

All Lagrange multipliers are equal to 0.0000 except that $\lambda_{12}^{2*} = 468.4277$. The incurred supply prices in Ukraine in hryvnia at the equilibrium are:

$$\pi_1^1(s^*) = 7,099.0347 = \$258.5048, \quad \pi_1^2(s^*) = 6,780.4995 = \$246.9056.$$

Ukrainian farmers are essentially selling their wheat at lower prices to compensate for the higher cost of transportation after the start of the invasion. In the later months after the start of the war, the supply price for Ukrainian wheat went as low as less than $100.

Example 2: Early Period Post-Full-Scale Invasion of February 24, 2022

The incurred demand prices at the equilibrium in Lebanon in Lebanese pounds are:

$$\rho_1^1(d^*) = 569,879.0000 = \$376.9041, \quad \rho_1^2(d^*) = 6,052.5005 = \$384.7743,$$

whereas the corresponding demand prices in Egypt in Egyptian pounds are:

$$\rho_2^1(d^*) = 574,560.0000 = \$380, \quad \rho_2^2(d^*) = 5,980.0000 = \$380.1652.$$

We observe that the demand prices in both demand country markets are now higher than in Example 1. In later months, close to the establishment of the Black Sea Grain Initiative, demand prices in Lebanon and Egypt reached high levels, even around $500; here, however, the markets are just starting to react to the war in terms of higher prices and the associated supply and transportation challenges.

Example 3: Black Sea Grain Initiative in Place

In this example, we consider the scenario in which the Black Sea Grain Initiative is in place (beginning in August).

The modified projection method yields the following equilibrium commodity shipment pattern:

$$Q_{11}^{11*} = 477,651.1563, \quad Q_{12}^{11} = 552,348.4375, \quad Q_{11}^{12*} = 0.0000, \quad Q_{12}^{12*} = 0.0000,$$

$$Q_{11}^{21*} = 0.0000, \quad Q_{12}^{21*} = 0.0000, \quad Q_{11}^{22*} = 0.0000, \quad Q_{12}^{22*} = 0.0000.$$

Once again, only efficient maritime routes are used for the transport of grains. The wheat commodity flows are improved compared to Example 2, especially in the case of Lebanon. Furthermore, as in Example 2, no corn is produced, which is, again, due to the high dependency of Lebanon and Egypt on Ukrainian wheat and Ukraine's war-induced limited supply capacity.

Example 3: Black Sea Grain Initiative in Place

The equilibrium commodity supplies and demand are:

$$s_1^{1*} = 999,999.6250, \quad s_1^{2*} = 0.0000.$$
$$d_1^{1*} = 447,651.1563, \quad d_1^{2*} = 0.0000,$$
$$d_2^{1*} = 552,348.4375, \quad d_2^{2*} = 0.0000.$$

The computed equilibrium Lagrange multipliers are all equal to 0.0000 except that $\mu_1^{1*} = 591.6817$ since, essentially, the supply output of commodities is at the capacity $\bar{S}_1^1 = 1,000,000.00$.

The incurred supply prices in Ukraine in hryvnia at the equilibrium are:

$$\pi_1^1(s^*) = 3,500.6001 = \$95.7269, \quad \pi_1^2(s^*) = 4,095.5000 = \$111.9949.$$

The price share of Ukrainian farmers is less than $100, even with the establishment of the Black Sea Grain Initiative and the facilitation of the transport of grains from Ukrainian Black Sea ports. This could be traced back to transportation costs remaining high even after the Initiative.

Example 3: Black Sea Grain Initiative in Place

The incurred demand prices at the equilibrium in Lebanon in Lebanese pounds are:

$$\rho_1^1(d^*) = 729,014.8125 = \$482.1526, \quad \rho_1^2(d^*) = 718,256.3750 = \$475.0372,$$

whereas the corresponding demand prices in Egypt in Egyptian pounds are:

$$\rho_2^1(d^*) = 9,738.2344 = \$508.5239, \quad \rho_2^2(d^*) = 9,900.5000 = \$516.9973.$$

Even though the transportation capacity limitations are lifted, one can see that, again, because of the high transportation costs and limited supply capacity, the demand prices remain at such high levels.

Sensitivity on Exchange Rates

Here, we conduct sensitivity analysis on the exchange rates, and we report the equilibrium supplies of the commodities of wheat and corn.

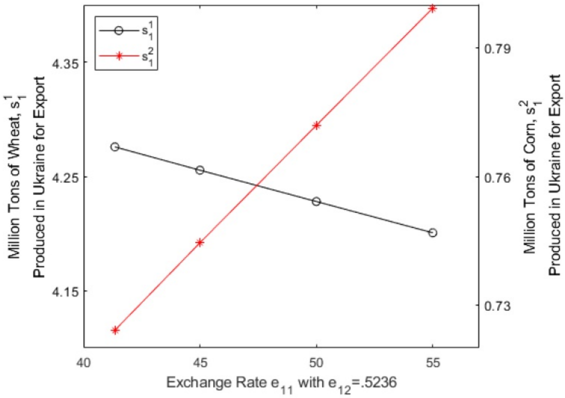


Figure: e_{12} fixed but with e_{11} Varying: Impact on Commodity Supplies

Sensitivity on Exchange Rates

• Note that, as seen in the above figure, with the depreciation of the Lebanese pound with respect to Ukrainian hryvnia, that is, higher rates of e_{11}, while keeping e_{12} fixed, the production of wheat in Ukraine decreases, and the supply of Ukrainian corn increases with a sharper slope. In other words, with less demand from Lebanon because of the depreciation of LBP, Ukraine meets the demand for wheat in Egypt and shifts to produce more corn to satisfy the demand for corn in Egypt.

• It should be noted that, generally, the supply and demand of wheat are more price inelastic than corn; furthermore, when there is a global deficit, resulting in food security concerns, the trade volumes of wheat are even less sensitive to exchange rate fluctuations.

Sensitivity on Exchange Rates

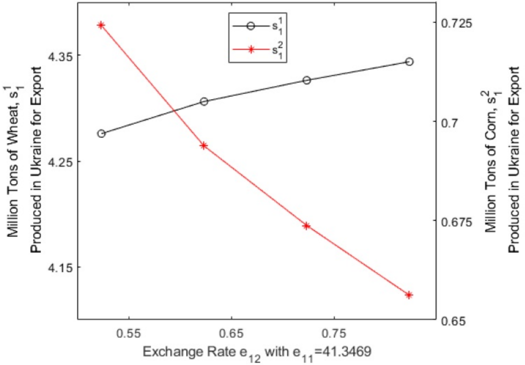


Figure: e_{11} fixed but with e_{12} Varying: Impact on Commodity Supplies

Sensitivity on Exchange Rates

• We observe that, as shown in the figure, with the depreciation of the Egyptian pound, with the Lebanese pound fixed, the supply of Ukrainian wheat increases, and the production of Ukrainian corn decreases, both at a decreasing rate.

• Essentially, with the depreciation of EGP, Egypt cannot afford as much Ukrainian grain as before, and Lebanon, which has a much higher demand for Ukrainian wheat than corn, imports more wheat. However, with the value of EGP going lower, and more wheat commodity flow appropriated by Lebanon, the country's demand for wheat is satisfied; it slowly shifts toward buying more corn, as such, causing a decreasing rate of decrease in the production of Ukrainian corn and a decreasing rate of increase in the production of Ukrainian wheat.

• Wheat has a lower price elasticity compared to corn, and corn plantings could have more variations based on the market conditions.

Insights & Summary

• We see that there is essentially no efficient alternative to the maritime transportation of grains from Ukrainian Black Sea ports, highlighting the importance of extending the Black Sea Grain Initiative during wartime to keep the transportation capacity sufficient not to disrupt the food security of demand country markets.

• The results confirm how the war has driven the earnings of the Ukrainian farmers, that is, the supply prices, to unprecedented low levels, possibly requiring the Ukrainian government's and global support of Ukrainian farmers for future harvest seasons, given the importance of Ukrainian grain to global food security, especially in the MENA region.

• The numerical results show the priority of wheat over corn in all scenarios in the demand markets of Lebanon and Egypt, as two countries representative of the MENA region.

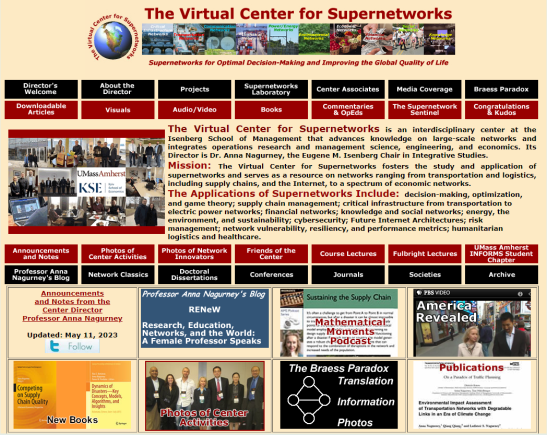
Insights & Summary

• **We find that Lebanon and Egypt compete over the war-induced limited production capacity at war-induced high prices to meet their populations' nutritional and caloric demands.**

• **The results demonstrate how the war-induced reduced production capacity in Ukraine intensifies this competition for meeting the fundamental need for food security of the Lebanese and Egyptian people.**

• **The economic instability of the demand country markets, in the form of the depreciation of their currencies, lowers their share of the Ukrainian wheat supply, causing food security concerns in these countries.**

• **The solutions to the numerical examples show the shift in the percentage of the limited production capacity in Ukraine utilized for producing each of the commodities of wheat and corn as the currency of each of the demand country markets depreciates.**



More information on our work can be found on the Supernetwork Center site: https://supernet.isenberg.umass.edu/