# Agricultural Trade and Ukraine in Wartime


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**Second International Virtual Conference on Ukraine**
**August 22-23, 2025**
**KTH, Stockholm, Sweden**

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# Acknowledgments

**Many thanks to KTH and to the organizers of this conference and to the speakers.**

**This presentation is dedicated to the farmers in Ukraine.**

# Outline of This Presentation

- **Background and Motivation**
- **Ukraine and Agricultural Trade**
- **Trade Policies and Exchange Rates**
- **The Multicommodity International Trade Model**
- **Making a Positive Impact**

# Background and Motivation

# I Work on the Modeling of Network Systems

# Much of My Recent Research Has Been on Supply Chains

# Some of My Books

# International Trade

**International trade provides us with commodities throughout the year and has benefits for producers and consumers alike.**

# Supply Chains Are Essential to Global Trade

- **Global supply chain networks** have made possible the wide distribution of goods, from agricultural products to textiles and apparel as well as aluminum and steel.
- Nations engage in trade to increase their productivity levels, employment rates, and general economic welfare.
- The increased level of world trade has also garnered **the attention of government policy makers**.
- Governments may attempt to protect their domestic firms from the possible effects of the **highly competitive** global arena.

# International Agricultural Trade

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

# Ukraine and Agricultural Trade

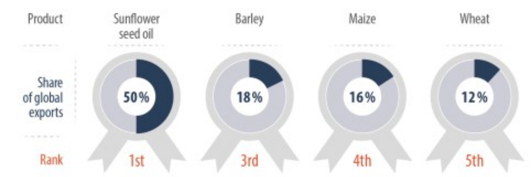
# Ukraine

**Ukraine is known as the breadbasket of Europe, thanks to its black "chernozem" soil, which is highly fertile and rich in organic matter called humus.**

**Covering more than half the landmass of Ukraine, chernozem soil is among the most fertile on planet earth and offers exceptional agronomic conditions for the production of a large range of crops, especially cereals and oilseeds. Ukraine has about 1/4 of the earth's chernozem.**

**According to Countryman et al. (2024), in 2021, primary agriculture contributed almost 10% of Ukraine's Gross Domestic Product (GDP), 18% of employment, and 44% of total export value.**

Ukraine's share of global agricultural exports and rank prior to the full-scale invasion




Council of the EU, 2022

- **Ukraine was also a major supplier of wheat to the World Food Programme (WFP) at more than 40%.**

# Ukraine in Wartime

**In a recent OECD (2025) report that cites a paper by Nivievskyi, Goriunov, and Nagurney (2024), the full-scale invasion by Russia on Ukraine of February 24, 2022, has negatively affected the agricultural sector through multiple channels:**

- **Large areas of agricultural land have been temporarily occupied or are unavailable due to the proximity to the frontline, mining, and contamination.**

- **The productivity of farmland in some areas has fallen through damage to soil cover caused by shelling and the movement of military equipment across farmland, damage to agricultural infrastructure such as drainage, irrigation and storage, the contamination or loss of water supplies previously abstracted for agriculture, and the destruction of agricultural machinery.**

# Ukraine in Wartime

- **The ability to export agricultural products was compromised, particularly in 2022 and 2023, due to the Russian attacks on shipments of goods through the Black Sea, and on grain storage and port facilities.**

- **Other logistical challenges have also hindered exports directly into Europe by land.**

- **The total income lost by Ukraine's farmers due to the war stands at $70bn, according to the KSE Institute.**

- **According to the latest review by the Kyiv School of Economics (KSE) for the Third Rapid Damage and Needs Assessment (RDNA) report, as of December 2023, Ukrainian agriculture had sustained $80 billion in damages and losses.**

# Ukraine in Wartime

Ukraine's agricultural sector continues to be a driving force behind the country's economy.

The performance of Ukraine's farms has become increasingly crucial to the country's wider economy during the war. Agricultural goods accounted for 60% of the country's exports in 2024, generating almost $25bn in foreign exchange earnings – up significantly from their pre-war level of 40%.

While many of Ukraine's major extractive and industrial centers have been occupied or destroyed by Russian aggression, the country's farmland has shown remarkable resilience.

As a critical contributor to global food security, and a key sector in Ukraine's economy, agriculture is a top priority for reconstruction efforts. KSE estimates that rebuilding Ukrainian agriculture will cost $56.1 billion in reconstruction and recovery needs.

# UMass Amherst and KSE Partnership

**In March 2022, UMass Amherst and KSE established a global partnership.**


**The partnership includes a Virtual Scholar in Residence Program and exchange students from KSE.**

# Some of Our Papers with KSE Colleagues

# Disasters and Food Security

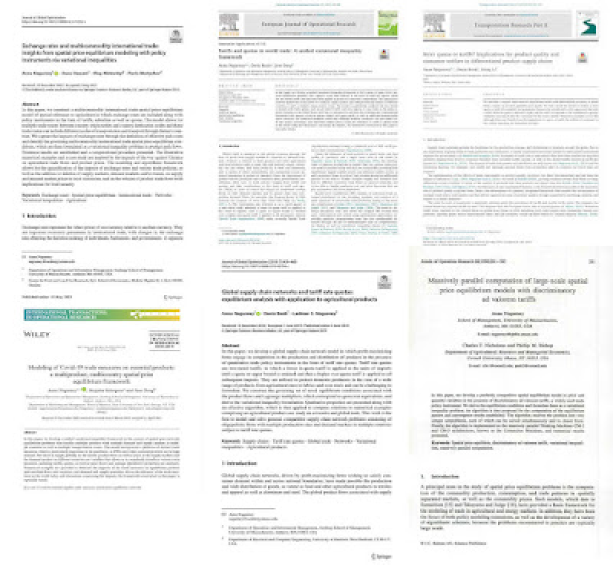
- **Climate change and COVID-19 impacted the affordability and accessibility of agri-food products around the globe.**
- **With the added disruptions of Russia's full-scale invasion of Ukraine, around 47 million people are estimated to have been added to the more than 276 million who were already facing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

# Trade Policies and Exchange Rates

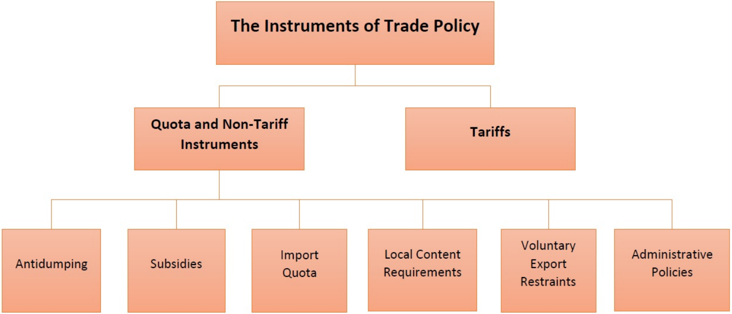
# International Trade and Policies

- **Nations engage in trade to increase their productivity levels, employment rates, and general economic welfare.**
- **The increased level of world trade and competition has garnered the attention of government policy makers.**
- Trade policy instruments such as tariffs, subsidies, and quotas have become highly relevant as the world continues to battle the impacts of the COVID-19 pandemic and millions on the planet suffer from hunger and growing food insecurity.

# Some of Our Papers on Tariffs

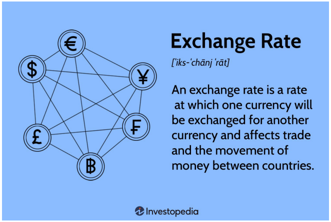


Identifying quantitatively the **impacts of trade policies and exchange rates** on international trade can provide trade and regulatory bodies with valuable information on product trade volumes and producer and consumer prices.



# Exchange Rates

**Exchange rates represent the value (price) of one currency relative to another currency.**




**They are important economic parameters in international trade, with changes in the exchange rate affecting the decision-making of individuals, businesses, and governments.**

# Exchange Rates

• The US dollar got stronger in 2022, with the greatest rate of increase occurring since the Russian invasion of Ukraine on February 24, 2022.

• In contrast, during the first year of the COVID-19 pandemic, the dollar weakened with respect to the euro, the British pound, and the yen.

# The Multicommodity International Trade Model

# The Model

**A. Nagurney, D. Hassani, O. Nivievskyi, and P. Martyshev, "Exchange Rates and Multicommodity International Trade: Insights from Spatial Price Equilibrium Modeling with Policy Instruments via Variational Inequalities,"** *Journal of Global Optimization* **87 (2023), pp 1-30.**


Journal of Global Optimization
https://doi.org/10.1007/s10898-023-01292-x


### Exchange rates and multicommodity international trade: insights from spatial price equilibrium modeling with policy instruments via variational inequalities


Anna Nagurney[1] · Dana Hassani[1] · Oleg Nivievskyi[2] · Pavlo Martyshev[2]



Received: 29 December 2022 / Accepted: 2 May 2023




**Abstract**

In this paper, we construct a multicommodity international trade spatial price equilibrium model of special relevance to agriculture in which exchange rates are included along with policy instruments in the form of tariffs, subsidies as well as quotas. The model allows for multiple trade routes between country origin nodes and country destination nodes and these trade routes can include different modes of transportation and transport through distinct countries. We capture the impacts of exchange rates through the definition of effective path costs and identify the governing multicommodity international trade spatial price equilibrium conditions, which are then formulated as a variational inequality problem in product path flows. Existence results are established and a computational procedure presented. The illustrative numerical examples and a case study are inspired by the impacts of the war against Ukraine on agricultural trade flows and product prices. The modeling and algorithmic framework allows for the quantification of the impacts of exchange rates and various trade policies, as well as the addition or deletion of supply markets, demand markets and/or routes, on supply and demand market prices in local currencies, and on the volume of product trade flows with implications for food security.



**Keywords** Exchange rates · Spatial price equilibrium · International trade · Networks · Variational inequalities · Agriculture


#### 1 Introduction

Exchange rates represent the value (price) of one currency relative to another currency. They are important economic parameters in international trade, with changes in the exchange rate affecting the decision-making of individuals, businesses, and governments. A separate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Published online: 15 May 2023


Springer

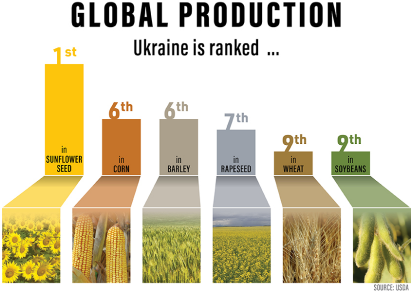
# The Model

**In this paper, we harness the powerful theory of variational inequalities to construct a model with the following features:**

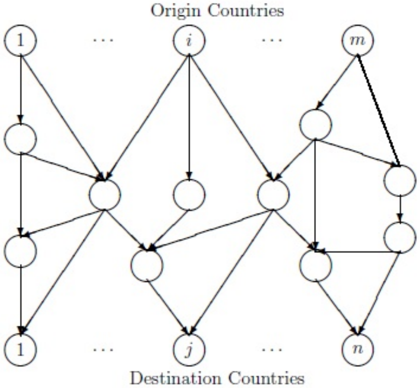
- **Multiple commodities**;
- **Multiple routes from origin nodes to destination nodes** in the same or different countries;
- **Exchange rates** and the formula for their computation along trade routes;
- Inclusion of policies in the form of **tariffs, subsidies, and quotas**;
- The underlying **economic functions can be nonlinear and asymmetric**. Hence, our **transportation cost functions capture congestion**.

# Additional Motivation

**This work is inspired by Russia's war on Ukraine and the need to assess its impacts on agricultural trade as well as on food insecurity and the need to provide more general computable models for assessing the impacts of trade policies and exchange rates on international trade.**



# The Multicommodity International Trade Model




The network topology is denoted by the graph $G = [N, L]$, where $N$ is the set of nodes, $L$ is the set of links, and $P$ is the set of paths. There are $H$ commodities, with a typical one denoted by $h$.

# The Multicommodity International Trade Model

Each path $p$ represents a trade route. Intermediate nodes in the network, which are transit points, also correspond to countries.

Let $P_{ij}$ denote the set of paths connecting the pair of origin/destination country nodes $(i, j)$. The paths are acyclic.

A typical link is denoted by $a$ and represents transport from a country node at which the link originates to the node denoting the country at which the link terminates.

**A trade route can entail transportation through multiple countries, depending on the application, and via different modes, such as rail, truck, air, or water (sea, river, etc.).**

# The Exchange Rates

Associated with each link $a \in L$ is an exchange rate $e_a$, reflecting the exchange rate from the country (node) that the link emanates from to the country (node) that it terminates in.

Also, associated with each pair of origin/destination countries $(i, j)$ is the exchange rate $e_{ij}$ for $i = 1, \ldots, m$; $j = 1, \ldots, n$.

# The Trade Policies

There is a nonnegative subsidy associated with commodity $h$ and imposed by the government in country $i$, which is denoted by $sub_i^h$ for $h = 1, \dots, H$; $i = 1, \dots, m$.

The unit tariff levied by country $j$ on commodity $h$ from country $i$ is denoted by $\tau_{ij}^h$ for $h = 1, \dots, H$; $i = 1, \dots, m$; $j = 1, \dots, n$. Tariffs within a country are not imposed; hence, $\tau_{ii}^h = 0$, $\forall i$, $\forall h$.

In addition, there are capacities, which can represent quotas, where $\bar{Q}_p^h$; $h = 1, \dots, H$; $p \in P$, denotes the bound on the commodity shipment of commodity $h$ on path $p$.

# Variables and Constraints

All commodity path flows, for all commodities $h$, and all paths $p$, must be nonnegative:

$$Q_p^h \geq 0, \quad \forall h, \forall p \in P. \tag{1}$$

The flow on a link $a$ of commodity $h$, in turn, is equal to the sum of the path flows of the commodity $h$ that use the link:

$$f_a^h = \sum_{p \in P} Q_p^h \delta_{ap}, \quad \forall h, \forall a \in L. \tag{2}$$

where $\delta_{ap} = 1$, if link $a$ is contained in path $p$, and is 0, otherwise.

# Variables and Constraints

The supply of commodity $h$ produced in country $i$, $s_i^h$, is equal to the shipments of the commodity from the country to all destination countries:

$$s_i^h = \sum_{p \in P^i} Q_p^h, \quad h = 1, \ldots, H; i = 1, \ldots, m, \tag{3}$$

whereas the demand for commodity $h$ in country $j$, $d_j^h$, is equal to the shipments of the commodity from all origin countries to that country:

$$d_j^h = \sum_{p \in P_j} Q_p^h, \quad h = 1, \ldots, H; j = 1, \ldots, n. \tag{4}$$

$Q \in R_+^{n_P}$ is the vector of commodity shipments with $s \in R_+^{Hm}$ being the vector of commodity supplies and $d \in R_+^{Hn}$ being the vector of commodity demands.

# Supply Price Functions

The supply price function for commodity $h$ of country $i$ is denoted by $\pi_i^h$ and we have that:

$$\pi_i^h = \pi_i^h(s), \quad h = 1, \ldots, H; i = 1, \ldots, m. \tag{5a}$$

With notice of the conservation of flow equations (3), we may define new supply price functions $\tilde{\pi}_i^h$; $h = 1, \ldots, H$; $i = 1, \ldots, m$, such that

$$\tilde{\pi}_i^h(Q) \equiv \pi_i^h(s). \tag{5b}$$

# Demand Price Functions

The demand price functions, in turn, are:

$$\rho_j^h = \rho_j^h(d), \quad h = 1, \ldots, H; j = 1, \ldots, n, \tag{6a}$$

where $\rho_j^h$ denotes the demand price for commodity $h$ in country $j$. Making use now of conservation of flow equations (4), we construct equivalent demand price functions $\tilde{\rho}_j^h$; $h = 1, \ldots, H$; $j = 1, \ldots, n$, as follows:

$$\tilde{\rho}_j^h(Q) \equiv \rho_j^h(d). \tag{6b}$$

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# Transportation Cost Functions

With each link $a \in L$, and commodity $h$, we associate a unit transportation cost $c_a^h$ such that

$$c_a^h = c_a^h(f), \quad \forall h, \forall a \in L. \tag{7a}$$

Because of the conservation of flow equations (2), we can define link unit transportation cost functions $\tilde{c}_a^h(Q)$, $\forall a \in L$, $\forall h$, as:

$$\tilde{c}_a^h(Q) \equiv c_a^h(f). \tag{7b}$$

# The Effective Exchange Rate

Observe that, in order to appropriately quantify the effective transportation cost on a link $a$ for a commodity $h$, if a commodity makes use of the link on a path from an origin country node to a destination country node, one needs to calculate the effective exchange rate associated with the commodity on link $a$ being transported onward on path $p$, which is denoted by $e_a^p$. Note that $e_a^p$ is the product of the exchange rates on the links on path $p$ that include and follow link $a$ on that path, and is given by:

$$e_a^p \equiv \begin{cases} \prod_{b \in \{a' \geq a\}_p} e_b, & \text{if } \{a' \geq a\}_p \neq \emptyset, \\ 0, & \text{if } \{a' \geq a\}_p = \emptyset, \end{cases} \tag{8}$$

where $\{a' \geq a\}_p$ denotes the set of the links including and following link $a$ in path $p$, and $\emptyset$ denotes the null set.

# The Effective Transportation Cost

The true transportation cost then on link $a$, $a \in L$, for commodity $h$; $h = 1, \dots, H$, when it is used in a path $p$, is given by the expression:

$$\tilde{c}_a^{hp} = \tilde{c}_a^h(Q)e_a^p. \tag{9}$$

The effective transportation cost on a path, $\tilde{C}_p^h$, $\forall p \in P$, for commodity $h$; $h = 1, \dots, H$, is then calculated as:

$$\tilde{C}_p^h = \sum_{a \in L} \tilde{c}_a^{hp} \delta_{ap}; \tag{10}$$

that is, the effective transportation cost on a path, which represents a trade route, is equal to the sum of the effective transportation costs for the commodity on links that make up the path.

**Definition 1: The Multicommodity International Trade Equilibrium Conditions**

*A multicommodity path trade flow pattern $Q^* \in R_+^{n_P}$ is an international trade spatial price network equilibrium pattern under subsidies and tariffs with explicit exchange rates and capacities if the following conditions hold: For all pairs of country origin and destination nodes: $(i, j)$; $i = 1, \ldots, m$; $j = 1, \ldots, n$, and all paths $p \in P_{ij}$ as well as all commodities $h$; $h = 1, \ldots, H$:*

$$(\tilde{\pi}_i^h(Q^*) - sub_i^h + \tau_{ij}^h)e_{ij} + \tilde{C}_p^h(Q^*) \begin{cases} \leq \tilde{\rho}_j^h(Q^*), & \text{if} \quad Q_p^{h*} = \bar{Q}_p^h, \\ = \tilde{\rho}_j^h(Q^*), & \text{if} \quad 0 < Q_p^{h*} < \bar{Q}_p^h, \\ \geq \tilde{\rho}_j^h(Q^*), & \text{if} \quad Q_p^{h*} = 0. \end{cases} \tag{11}$$

# Variational Inequality Formulation and Existence

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

*A multicommodity path trade flow pattern* $Q^* \in K$, *where* $K \equiv \{Q | 0 \leq Q \leq \bar{Q}\}$ *is a multicommodity international trade spatial price network equilibrium pattern with exchange rates and under subsidies and tariffs and capacities, according to Definition 1, if and only if it satisfies the variational inequality:*

$$\sum_{h=1}^{H} \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{p \in P_{ij}} \left[ (\tilde{\pi}_i^h(Q^*) - sub_i^h + \tau_{ij}^h) e_{ij} + \tilde{C}_p^h(Q^*) - \tilde{\rho}_j^h(Q^*) \right]$$

$$\times \left[ Q_p^h - Q_p^{h*} \right] \geq 0, \quad \forall Q \in K. \qquad (12)$$

**Existence of an equilibrium solution** $Q^*$ **is guaranteed since the feasible set** $K$ **is compact.**

# 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

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

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

Specifically, we define $X \equiv Q$, $\mathcal{K} \equiv K$, and $\mathcal{N} = Hn_P$. Plus, $F(X)$ consists of the elements

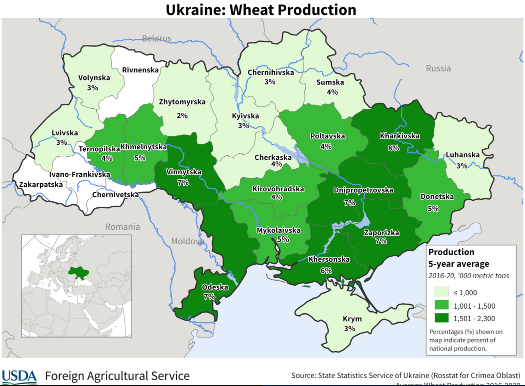
$F_p^h(X) \equiv \left[ (\tilde{\pi}_i^h(Q) - sub_i^h + \tau_{ij}^h) e_{ij} + \tilde{C}_p^h(Q) - \tilde{\rho}_j^h(Q) \right]$, $\forall h$, $\forall i, j$, $\forall p \in P_{ij}$. Clearly, VI (12) can be put into standard form (13).

# Illustrative Examples

# Illustrative Examples

The examples focus on wheat commodity flows from Ukraine to Lebanon before and after the invasion of Ukraine by Russia on February 24, 2022.

The local currency codes are: UAH for Ukrainian hryvnia, MDL for the Moldovan leu, RON for the Romanian leu, LBP for the Lebanese pound, and USD for the United States dollar.



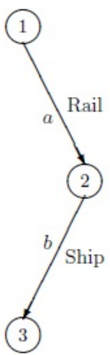
# Illustrative Examples

The unit of flow is a ton of wheat.

In these examples, there are no commodity path flow capacities.

These illustrative examples are stylized but, nevertheless, are grounded in real data.

# Example 1 - Pre-Invasion Scenario




The network topology for Illustrative Example 1 with nodes 1 and 2 representing Ukraine and node 3 corresponding to Lebanon. There is a single path $p_1 = (a, b)$, where link $a$ corresponds to transport to the Black Sea ports via rail inside Ukraine, and link $b$ represents maritime transport from the Black Sea ports to Lebanon.

# Example 1 - Pre-Invasion Scenario

The exchange rate data for Example 1 is drawn from early January 2022:

$$e_{13} = 55.0581, \quad e_a = 1.0000, \quad e_b = 55.0581.$$

The supply price function in Ukraine in hryvnia is:

$$\pi_1 = \pi_1(s_1) = .000136 s_1 + 7,001.60.$$

The transportation cost functions in local currencies are:

$$c_a = c_a(f_a) = .000278 f_a + 954.80, \quad c_b = c_b(f_b) = .000278 f_b + 1,091.20.$$

The demand price function in Lebanon in Lebanese pounds is:

$$\rho_3 = \rho_3(d_3) = -.15 d_3 + 602,344.00.$$

The effective exchange rates and the effective link costs are:

$$e_a^{p_1} = e_a e_b = 55.0581, \quad e_b^{p_1} = 55.0581,$$

$$\tilde{c}_a^{p_1} = e_a^{p_1} \tilde{c}_a = 55.0581 \tilde{c}_a, \quad \tilde{c}_b^{p_1} = e_b^{p_1} \tilde{c}_b = 55.0581 \tilde{c}_b.$$

The effective path cost on path $p_1$ is:

$$\tilde{C}_{p_1} = \tilde{c}_a^{p_1} + \tilde{c}_b^{p_1}.$$

Applying the international trade spatial price equilibrium conditions (11), under the assumption of no tariff and no subsidy, and no quota, and assuming that $Q^*_{p_1} > 0$, we have that:

$$\tilde{\pi}_1(Q^*_{p_1})e_{13} + \tilde{C}_{p_1}(Q^*_{p_1}) = \tilde{\rho}_3(Q^*_{p_1}),$$

which, in turn, reduces to:

$$.1881 Q^*_{p_1} = 104,200.3344,$$

with solution:

$$Q^*_{p_1} = 553,962.4370.$$

**The** $553,962.4370$ **tons of wheat flow is quite reasonable, since, in 2021, Lebanon imported** $520,000$ **tons of wheat from Ukraine, and an even greater harvest was expected in 2022.**

# Example 1 - Pre-Invasion Scenario

The above wheat commodity flow pattern results in a supply and a demand of:

$$s_1^* = d_3^* = Q_{p_1}^* = 553,962.4370.$$

The supply and demand prices are:

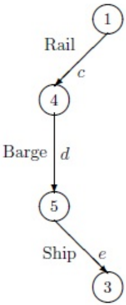
$$\pi_1(s_1^*) = \tilde{\pi}_1(Q_{p_1}^*) = 7,076.9388 \text{ UAH} = \$257.7002,$$
$$\rho_3(d_3^*) = \tilde{\rho}_3(Q_{p_1}^*) = 519,249.6344 \text{ LBP} = \$343.4190.$$

The incurred transportation costs are:

$$\tilde{c}_a = 1,108.8015 \text{ UAH} = \$40.3759, \quad \tilde{c}_b = 1,245.2015 \text{ UAH} = \$45.3428.$$

**The supply price of** \$257.7002 **per ton of wheat in Ukraine (at the farmer level) and the demand price of** \$343.4190 **in Lebanon are close to the reported prices in 2021. Farmers in Ukraine could get about** \$270 **per ton of wheat before the invasion. The transportation cost pre-invasion for a ton of wheat in Ukraine to a port was about** \$40**, as is the result in this example.**

# Example 2 - Invasion Scenario




**In Example 2, we consider the invasion scenario after February 24, 2022, but before the Black Sea Grain Initiative, which took effect in late July.** During this period, essentially no grain was shipped from Ukraine using a Black Sea route as in Example 1. There is a single path $p_2 = (c, d, e)$. Nodes 1, 3, 4, and 5 denote Ukraine, Lebanon, Moldova, and Romania, respectively.

# Example 2 - Invasion Scenario

The exchange rates for Example 2 are obtained from early July; that is, after the invasion but before the Black Sea Grain Initiative:

$$e_{13} = 51.6836, \quad e_c = .6528, \quad e_d = .2523, \quad e_e = 313.6980,$$

The exchange rates were essentially the same on July 20, 2022.

The supply price function in Ukraine in hryvnia is:

$$\pi_1(s) = \pi_1(s_1) = .002673 s_1 + 2,806.30.$$

**The difference in supply price function compared to the function in Example 1 is due to the damages because of the war.**

# Example 2 - Invasion Scenario

The transportation cost functions in local currencies are:

$$c_c = .002768 f_c + 6,546.50, \quad c_d = .002172 f_d + 2,324.60, \quad c_e = .000257 f_e + 345.40.$$

**The difference in the cost function on link $c$ in this example and the cost function on link $a$ in Example 1, with both entailing rail transportation in Ukraine, is due to the different rail gauges used in Ukraine and Moldova, which necessitates including loading and unloading costs. Loading and unloading costs are also accounted for in the cost function on link $d$.**

The demand price function in Lebanon in Lebanese pounds is:

$$\rho_3(d) = \rho_3(d_3) = -.17 d_3 + 793,747.50.$$

**Note that due to the food security issues in Lebanon and concerns over the availability of Ukrainian wheat because of the war, the demand price function is different from the one in Example 1.**

# Example 2 - Invasion Scenario

According to the international trade spatial price equilibrium conditions (11), and assuming that $Q^*_{p_2} > 0$, we have that:

$$\tilde{\pi}_1(Q^*_{p_2})e_{13} + \tilde{C}_{p_2}(Q^*_{p_2}) = \tilde{\rho}_3(Q^*_{p_2}),$$

the solution of which yields:

$$Q^*_{p_2} = 25,780.2589.$$

**The wheat flow of $25,780.2589$ tons is reasonable since, without access to deep-sea ports on the Black Sea, Ukraine can, at most, export around $10\%$ of what it used to.**

This commodity flow results in a supply and a demand of:

$$s^*_1 = d^*_3 = Q^*_{p_2} = 25,780.2589.$$

# Example 2 - Invasion Scenario

The supply and demand prices are:

$$\pi_1(s_1^*) = \tilde{\pi}_1(Q^*) = 2,875.2106 \text{ UAH} = \$98.2813,$$

$$\rho_3(d_3^*) = \tilde{\rho}_3(Q^*) = 789,364.8559 \text{ LBP} = \$522.0667.$$

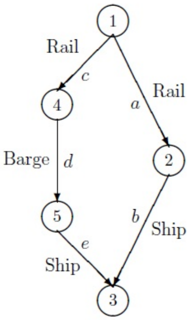
The incurred transportation link costs are:

$$\tilde{c}_c = 6,617.8597 \text{ UAH} = \$226.2137, \ \tilde{c}_d = 2,380.5947 \text{ MDL} = \$124.6358$$

$$\tilde{c}_e = 352.0255 \text{ RON} = \$73.0358.$$

**The transportation cost of grain inside Ukraine has jumped to about $200. Furthermore, because of the ongoing war, Ukrainian farmers are earning approximately $100 per ton of wheat, which is similar to the supply price of $98.2813 in this example. Moreover, with the continuing food crisis in Lebanon, and, as a result of the war, the price of wheat in Lebanon has gone up to more than $500 per ton.**

# Example 3 - Black Sea Grain Initiative in Place




**The network topology for Example 3, where we consider the post-July 22 Black Sea Grain Initiative scenario with maritime transportation from several of the Ukrainian Black Sea ports being, again, possible.** In the network above, the nodes and the links correspond to the same countries and modes of transportation as in Examples 1 and 2.

# Example 3 - Black Sea Grain Initiative in Place

The exchange rates on links are from late August; that is, after the Black Sea Grain Initiative:

$$e_a = 1.0000, \quad e_b = 41.3469, \quad e_c = .5291,$$

$$e_d = .2521, \quad e_e = 309.8670, \quad e_{13} = 41.3469.$$

The exchange rates were essentially the same on July 22, 2022.

The supply price function in Ukrainian hryvnia is now:

$$\pi_1(s) = \pi_1(s_1) = .000167 s_1 + 3,364.60.$$

**Observe that due to the damages by the ongoing war, the supply price function, again, changes from the ones in Examples 1 and 2.**

# Example 3 - Black Sea Grain Initiative in Place

The transportation cost functions in local currencies are:

$$c_a = .000217 f_a + 7,144.80, \quad c_b = .000246 f_b + 7,423.10,$$

$$c_c = .003284 f_c + 8,304.80, \quad c_d = .003097 f_d + 2,397.50,$$

$$c_e = .000428 f_e + 361.20.$$

**The damages to the transportation infrastructure, and the congestion associated with products to be exported after the placement of the Black Sea Grain Initiative, result in different transportation cost functions from the previous examples.**

The demand price function in Lebanese pounds is:

$$\rho_3(d) = \rho_3(d_3) = -.082 d_3 + 796,162.50.$$

**The demand price function is different from Example 2, which is in correspondence to the food security issues in Lebanon.**

# Example 3 - Black Sea Grain Initiative in Place

The equilibrium conditions (11) are, for this example, assuming positive commodity shipments:

$$\tilde{\pi}_1(Q^*)e_{13}+\tilde{C}_{p_1}(Q^*_{p_1}) = \tilde{\rho}_3(Q^*), \quad \tilde{\pi}_1(Q^*)e_{13}+\tilde{C}_{p_2}(Q^*_{p_2}) = \tilde{\rho}_3(Q^*).$$

The solution of the above system of equations yields a negative path flow on path $p_2$, which is infeasible. Therefore, path $p_2$ is not used. Then, one has that: $Q^*_{p_1} = 506,566.8120$ and $Q^*_{p_2} = 0.0000$, with the commodity flows, again, in tons.

**The supply is similar to what Ukraine used to export to Lebanon pre-war. With the availability of maritime transportation from Ukraine on the Black Sea, the wheat flow on path $p_2$ is at $0.0000$, which is due to the inefficiency of transporting the grain to a Middle Eastern country by such a route and composition of modes.**

# Example 3 - Black Sea Grain Initiative in Place

This wheat commodity flow pattern results in the following supply and demand:

$$s_1^* = d_3^* = Q_{p_1}^* + Q_{p_2}^* = 506,566.8120,$$

with the supply and demand prices per ton now being:

$$\pi_1(s_1^*) = \tilde{\pi}_1(Q^*) = 3,449.1966 \text{ UAH} = \$94.3212,$$

$$\rho_3(d_3^*) = \tilde{\rho}_3(Q^*) = 754,624.0214 \text{ LBP} = \$499.0899.$$

The incurred transportation costs are:

$$\tilde{c}_a = 7,254.7249 \text{ UAH} = \$198.3867, \quad \tilde{c}_b = 7,547.7154 \text{ UAH} = \$206.3988,$$

$$\tilde{c}_c = 8,304.8000 \text{ UAH} = \$227.1019, \quad \tilde{c}_d = 2,397.5000 \text{ MDL} = \$123.9018,$$

$$\tilde{c}_e = 361.2000 \text{ RON} = \$74.0245.$$

**Although the initiative has facilitated the transportation of wheat, the war, has kept the demand price high. The supply price at** \$94.3212 **and the demand price at** \$499.0899**, along with the** \$206.3988 **transportation cost on link** $b$**, reflect these issues and are preventing the demand market prices from falling.**

**In Example 4, we, again, consider the post-July 22 Black Sea Grain Initiative scenario with maritime transportation via the Black Sea from Ukraine possible; however, a subsidy is introduced in this example, and the impact is quantified.** We consider the effect of the subsidy $sub_1 = 1,000.00$ in hryvnia on Ukrainian wheat shipped to Lebanon:

**In the solution of this example, again, only path $p_1$ is used, and one has that: $Q^*_{p_1} = 889,408.4787$ and $Q^*_{p_2} = 0.0000$.**

This wheat commodity flow pattern results in the following supply and demand:

$$s^*_1 = d^*_3 = Q^*_{p_1} + Q^*_{p_2} = 889,408.4787,$$

with the following supply and demand prices:

$$\pi_1(s^*_1) = \tilde{\pi}_1(Q^*) = 3,513.1312 \text{ UAH} = \$96.0696,$$

$$\rho_3(d^*_3) = \tilde{\rho}_3(Q^*) = 723,231.0047 \text{ LBP} = \$478.3273.$$

# Example 4 - Example 3 Data with Subsidy

The incurred transportation costs are:

$$\tilde{c}_a = 7,337.8016 \text{ UAH} = \$200.6585, \ \tilde{c}_b = 7,641.8944 \text{ UAH} = \$208.9742,$$

$$\tilde{c}_c = 8,304.8000 \text{ UAH} = \$227.1019, \ \tilde{c}_d = 2,397.5000 \text{ MDL} = \$123.9018$$

$$\tilde{c}_e = 361.2000 \text{ RON} = \$74.0245.$$

**The subsidy increases the quantity of wheat shipment, and increases the price that farmers can expect to get for a ton of wheat to** \$96.0696**, which is of value as the current low supply prices threaten the farmers' ability to buy seed and equipment for the next harvest season.**

**The subsidy also helps to reduce the demand price to** \$478.3273**, which can be of significant importance in countering the food crisis and associated food insecurity in Lebanon.**

# Insights

- **The importance of having alternative routes in countering disruptions and congestion** is evident in our examples.

- The results strongly confirm **the need for efficient transportation routes for trade**, as, for example, for the export of grain via maritime transport from the Black Sea ports in the case of Ukraine.

- The examples show the **benefits of subsidies for agricultural trade for both farmers and consumers**.

- **The impact of the exchange rates on the grain commodity flows and on producer and consumer prices are revealed** in the examples for different periods: pre-invasion, following the invasion, and after the Black Sea Grain Initiative.

- **The examples demonstrate the importance of the Ukrainian grain, and its relevance to global food security.**

# Some Additional Research

**A. Nagurney and E. Besedina, "A Multicommodity Spatial Price Equilibrium Model with Exchange Rate and Non-Tariff Measures,"** *Operations Research Forum* **4, Article number 84, 2023.**

**A. Nagurney, "Food Security and Multicommodity Agricultural International Trade: Quantifying Optimal Consumer Subsidies for Nutritional Needs,"** *International Transactions in Operations Research*, **2024, 31(3), pp 1375-1396.**

**M. Kushnir, A. Nagurney, and R. Konrad, "Civilian-Military Integration in Ukrainian Defense Supply Chain,"** *Proceedings of the 21st ISCRAM Conference* **– Münster, Germany, May 2024, B. Penkert et al. Editors.**

**D. Hassani, A. Nagurney, O. Nivievskyi, and P. Martyshev, "A Multiperiod, Multicommodity, Capacitated International Agricultural Trade Network Equilibrium Model with Applications to Ukraine in Wartime,"** *Transportation Science*, **2025, 59(1), pp 143-164.**

**A. Nagurney, I. Pour, and B. Kormych, "Integrated Crop and Cargo War Risk Insurance: Application to Ukraine,"** *International Transactions in Operations Research*, **2026, 33, pp 5-37.**

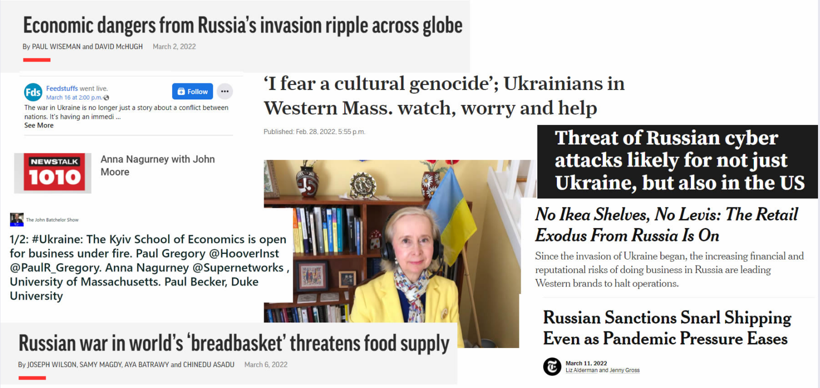
# Making a Positive Impact

# Responding to Media Requests on Tariffs

**I believe that it is important to respond to media requests on topics that your research can inform, such as that of our work on tariffs and trade.**


**Computable mathematical models and associated analyses on tariffs and trade can provide valuable insights (including unexpected ones) for policy-makers and decision-makers.**

# Some of the Media Interviews on the War on Ukraine


Economic dangers from Russia's invasion ripple across globe
By PAUL WISEMAN and DAVID McHUGH March 2, 2022

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'I fear a cultural genocide'; Ukrainians in Western Mass. watch, worry and help
Published: Feb. 28, 2022, 5:55 p.m.

Threat of Russian cyber attacks likely for not just Ukraine, but also in the US

*No Ikea Shelves, No Levis: The Retail Exodus From Russia Is On*
Since the invasion of Ukraine began, the increasing financial and reputational risks of doing business in Russia are leading Western brands to halt operations.

Russian Sanctions Snarl Shipping Even as Pandemic Pressure Eases
March 11, 2022
Liz Alderman and Jenny Gross

Russian war in world's 'breadbasket' threatens food supply
By JOSEPH WILSON, SAMY MAGDY, AYA BATRAWY and CHINEDU ASADU March 6, 2022

# Thank You Very Much!


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