Ad Valorem Tariffs in Global Supply Chain Networks and Impacts on Labor

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ABSTRACT

Global supply chain networks are essential to the production, trade, and consumption of commodities, including agricultural ones. Such networks have been increasingly impacted by trade policies, especially ad valorem tariffs, which are affecting commodity flows, prices, and profits. Furthermore, the labour market plays a critical role in the functioning of supply chain networks. However, the impacts of ad valorem tariffs on labour (and employment) have not yet been quantitatively examined in a competitive global supply chain network framework. This paper constructs an oligopolistic supply chain network equilibrium model that integrates ad valorem tariffs and labour. Firms compete noncooperatively in maximising their profits by determining their product flows across multiple production sites. Demand markets can be located in different countries, with production and shipment activities subject to labour upper bounds and wages. The governing Nash equilibrium conditions are formulated as a variational inequality. Through Lagrange analysis, an alternative variational inequality is derived with nice features for computations. Illustrative examples are provided along with a global soybean trade case study. Numerical results reveal how such tariffs shift trade flows, reshape labour allocation, and affect demand prices as well as profits, with labour shortages and cost disruptions further negatively compounding the effects.

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Supply chains; labour; tariffs; global trade; networks; variational inequalities

PRACTITIONER SUMMARY

Global supply chain networks form the backbone of international trade and trade flows by linking production sites to demand markets across countries through transportation. Some governments are, increasingly, attempting to alter the product trade flows by instituting policies in the form of tariffs. Tariffs can affect production and transportation decisions and modify demand prices as well as profits. At the same time, labour availability is central to the functioning of supply chain networks and, yet, labour considerations have often been absent from trade policy models. In this paper, we developed a competitive global supply chain network model that explicitly incorporates ad valorem tariffs, which are very common in practice, and labour constraints. Firms in the model have multiple production sites in different countries and ship products to multiple demand markets, with production and shipment activities requiring labour that is subject to site and route specific upper bounds. Wages can vary by location, and labour productivity factors translate labour input into output. Firms compete noncooperatively in product quantities and labour and seek to maximise their own profits. After providing illustrative numerical examples, which are solved analytically, we present a case study of the global soybean trade, focusing on the United States, Brazil, Argentina, and China. The case study numerical examples, whose solutions are computed *via* an algorithm, reveal the effects of the imposition of ad valorem tariffs, labour restrictions, and climate-related disruptions through changes in production cost functions. The computed equilibrium solutions show that ad valorem tariffs shift production and trade flows towards sources without ad valorem tariffs, alter labour allocation at production sites and along transportation routes, and increase demand prices for consumers. Labour constraints, whether from shortages or immigration policy restrictions, reduce product flows and profitability for the affected firms while creating competitive advantages for less constrained producers. When ad valorem tariffs and increased production cost disruptions occur together, their effects compound, leading to reduced trade flows, higher demand prices, and lower overall profits. The results offer important policy and managerial insights. For policymakers, the results highlight that ad valorem tariffs not only influence prices and trade flows but also interact with labour in shaping competitive outcomes. Ad valorem tariffs can shift market share across countries but may also reduce total output and increase consumer demand prices, particularly when implemented widely. For firms, our model highlights the advantage of diversifying production locations to mitigate the effects of ad valorem tariffs and labour disruptions.

Outline of Presentation

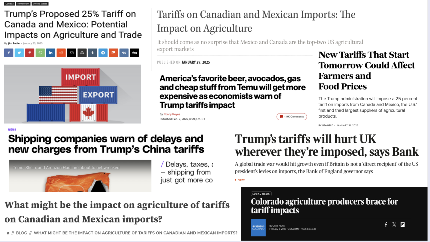
- **Introduction and Motivation**
- **Literature Review and Contributions**
- **Supply Chain Network Model with Labor and Tariffs**
- **Numerical Examples**
- **Insights and Summary**

Introduction and Motivation

The Reemergence of Tariffs in Global Trade

- The global economy is shifting rapidly, with tariffs reemerging as key trade policies, reshaping global supply chains and labor markets. The United States raised its average tariff rate from 2.5% in 2024 to 15.4% in 2025, the highest level since 1938.

- Tariffs raise costs for both consumers and firms. By raising the cost of imported inputs and final goods, tariffs force firms to rethink sourcing, drive up production costs, and, ultimately, raise consumer prices, reducing consumer welfare and leading to resource misallocation.



When Tariffs Hit Workers

- **Labor has become a critical, yet frequently overlooked, component of supply chains, with availability constraining throughput from manufacturing to transportation and warehousing.**

- **Labor markets in the US are already showing strain from these tariffs, with a projected 0.3% rise in unemployment and a loss of 376,000 payroll jobs by the end of 2025.**

Ad Valorem Tariffs and Labor: A Unified Framework

• **Ad valorem tariffs, calculated as a percentage of the imported good's value, have become especially prevalent, introducing nonlinearities into trade models and yielding distinct strategic and welfare implications.**

⇒ Given the prominence of ad valorem tariffs and the growing importance of labor in supply chains, understanding their joint impact requires a network-level perspective; however, very few studies integrate both within an oligopolistic framework.

Literature Review and Contributions

Literature Review

• The theory of variational inequalities (cf. **Nagurney (1999, 2006)**) is the methodology used to develop the modeling and algorithmic framework, with a classical application of spatial price equilibrium models (**Samuelson (1952)** and **Takayama and Judge (1964, 1971)).**

• **Nicholson et al. (1994)** and **Nagurney et al. (1996a, 1996b)** established foundational variational inequality formulations for spatial price equilibrium with ad valorem tariffs, demonstrating that nonlinearities make traditional optimization methods inadequate.

• Subsequent variational inequality based models have integrated:

- Unit tariffs along with rerouting to evade tariffs (**Nagurney and Samadi (2025)**),
- Unit tariffs and tariff-rate quotas within spatial price equilibrium models (**Nagurney (2022a), Nagurney et al. (2022), Nagurney et al. (2023), and Nagurney et al. (2019)**),
- Unit tariffs and tariff-rate quotas within oligopolistic frameworks (**Nagurney et al. (2019) and Nagurney et al. (2019)**).

Literature Review

• **Edwards (1988)** provided one of the earliest theoretical frameworks linking changes in the terms of trade and import tariffs to labor adjustment.

• **Nagurney (2021a)** was among the first to explicitly integrate labor into a perishable food supply chain network model using a variational inequality framework; **Nagurney (2021b, 2022b)** extended this to wage-dependent and wage-responsive labor models.

• Several recent studies highlight the labor effects of ad valorem tariffs: **Xu and Ouyang (2017), Benguria and Saffie (2020), and He et al. (2021).**

• **Ahmed et al. (2025)** develop a general oligopolistic equilibrium model to analyze how changes in specific tariffs affect wages and employment across sectors.

• **No existing study unifies ad valorem tariffs and labor constraints within a single variational inequality game-theoretic framework for oligopolistic supply chain networks.**

Contributions

- **Firms operate multiple production sites across countries and supply products to global demand markets under noncooperative competition, each maximizing its own profit under endogenous pricing and cost structures.**

- **Labor is modeled as a decision variable at production sites and along transportation routes, subject to site and route-specific bounds. Wages vary by location, capturing heterogeneity across global labor markets.**

- **Ad valorem tariffs are imposed on product flows between countries, directly influencing firms' decisions on labor allocation, product flows, and site selection.**

- **Nash equilibrium conditions are stated as a variational inequality; a Lagrange analysis yields an alternative formulation for large-scale networks.**

- **The framework is applied to the global soybean trade, capturing retaliatory ad valorem tariffs, immigration-driven labor shortages, and drought-induced cost disruptions.**

Supply Chain Network Model with Labor and Tariffs

The Global Supply Chain Network Topology

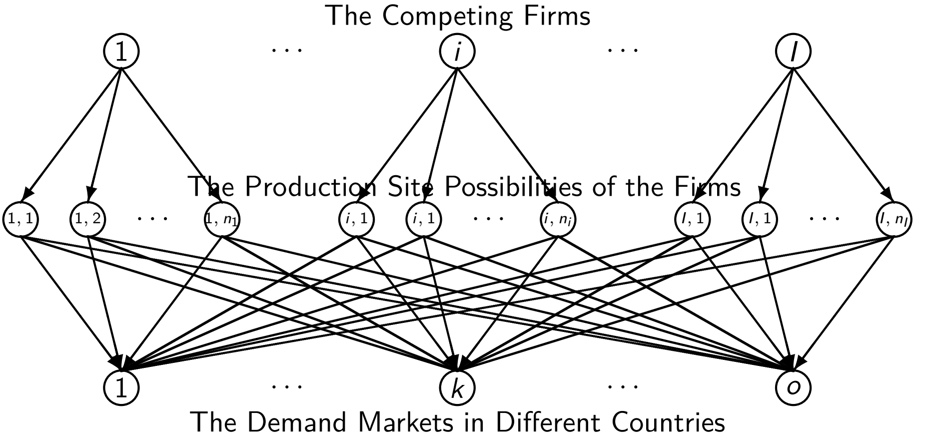


Figure: The Global Supply Chain Network with Ad Valorem Tariffs and Labor

Table: Notation for the Global Supply Chain Network Model with Tariffs

Variables	Definition
s^i_j	nonnegative production output (supply) of firm i at its production site j; $j = 1, \dots, n_i$. Group outputs for each i; $i = 1, \dots, I$, into vector $s^i \in R^{n_i}_+$ and all such vectors into $s \in R_+^{\sum_{i=1}^I n_i}$.
Q^i_{jk}	nonnegative amount of firm i's product produced at its site j and shipped to demand market k. The $\{Q^i_{jk}\}$ elements for all j and k are grouped into vector $Q^i \in R^{n_i o}_+$ and Q^i; $i = 1, \dots, I$, into $Q \in R_+^{\sum_{i=1}^I n_i o}$.
d^i_k	demand for firm i's product at demand market k. Group demands for firm i's product for each $i = 1, \dots, I$, into vector $d^i \in R^o_+$ and then group demands for all i into $d \in R^{Io}_+$.
l^i_j	labor (in hours) available at firm i's production site j; $i = 1, \dots, I$; $j = 1, \dots, n_i$.
l^i_{jk}	labor (in hours) available for shipping firm i's product for $i = 1, \dots, I$ from its production site j; $j = 1, \dots, n_i$ to market k; $k = 1, \dots, o$.

Table: Notation for the Global Supply Chain Network Model with Tariffs

Functions	Definition
$f^i_j(s)$	production cost at firm i's site j.
$\hat{c}^i_{jk}(Q)$	total transportation cost associated with shipping firm i's product, produced at site j, to demand market k.
$\rho^i_k(d)$	demand price function for firm i's product at demand market k.

Table: Notation for the Global Supply Chain Network Model with Tariffs

Parameters	Definition
w^i_j	hourly wage at firm i's production site j.
w^i_{jk}	hourly wage for shipping firm i's product from its production site j to demand market k.
β^i_j	positive factor relating inputs of labor at firm i's production site j to the amount of product produced there.
β^i_{jk}	positive factor relating inputs of labor to shipment volume of firm i's product from its site j to market k.
$\bar{l}^i_j$	upper bound on labor hours of availability at production site j of firm i.
$\bar{l}^i_{jk}$	upper bound on labor hours of availability for shipment of firm i's product produced at its site j to market k.
τ^i_{jk}	ad valorem tariff rate between country that production site j of firm i is in and country of market k

Conservation of Flow Equations

The production output at firm i's site j, s^i_j, is equal to the total shipments of firm i's product to all the demand markets; that is:

$$s^i_j = \sum_{k=1}^{o} Q^i_{jk}, \quad i = 1, \ldots, I; j = 1, \ldots, n_i, \tag{1}$$

whereas the demand for firm i's product at demand market k, d^i_k, must be satisfied by the firm's product shipments from all the firm's production sites to each demand market; hence:

$$d^i_k = \sum_{j=1}^{n_i} Q^i_{jk}, \quad i = 1, \ldots, I; k = 1, \ldots, o. \tag{2}$$

Furthermore, all the product shipments must be nonnegative:

$$Q^i_{jk} \geq 0, \quad i = 1, \ldots, I; j = 1, \ldots, n_i; k = 1, \ldots, o. \tag{3}$$

Relationship Between Labor and Productivity

Using an approach as in Nagurney (2023a, b), relating labor to production outputs, as in economics, we have that the relationships, under the assumption of linearity between product outputs and labor, are at the production sites, and in transportation, respectively, as follows:

$$s^i_j = \beta^i_j l^i_j, \quad i = 1, \dots, I; j = 1, \dots, n_i, \tag{4}$$

and

$$Q^i_{jk} = \beta^i_{jk} l^i_{jk}, \quad i = 1, \dots, I; j = 1, \dots, n_i; k = 1, \dots, o. \tag{5}$$

Also, the labor capacities cannot be exceeded, and the labor hours are nonnegative, so that

$$0 \leq l^i_j \leq \bar{l}^i_j, \quad i = 1, \dots, I; j = 1, \dots, n_i \tag{6}$$

and

$$0 \leq l^i_{jk} \leq \bar{l}^i_{jk}, \quad i = 1, \dots, I; j = 1, \dots, n_i; k = 1, \dots, o. \tag{7}$$

Optimization Problems of the Competing Firms

Each firm i; $i = 1, \ldots, I$, seeks to maximize its utility, U^i, consisting of its net revenue, subject to its constraints. Therefore, the optimization problem faced by each firm i; $i = 1, \ldots, I$, is given by:

$$\text{Maximize } U^i = \sum_{j=1}^{n_i} \sum_{k=1}^{o} \frac{\rho_k^i(d) Q_{jk}^i}{(1+\tau_{jk}^i)} - \sum_{j=1}^{n_i} f_j^i(s) - \sum_{j=1}^{n_i} \sum_{k=1}^{o} \hat{c}_{jk}^i(Q)$$

$$- \sum_{j=1}^{n_i} w_j^i l_j^i - \sum_{j=1}^{n_i} \sum_{k=1}^{o} w_{jk}^i l_{jk}^i \tag{8}$$

subject to: (1) – (7) for i.

The first term in (8) represents the revenue under the ad valorem tariff rate.

Some Reformulations

Because of expression (1), one can redefine the production cost functions (cf. Table 1) in terms of product shipments, thus:

$$\hat{f}_j^i = \hat{f}_j^i(Q) \equiv f_j^i(s), \quad i = 1, \ldots, I; j = 1, \ldots, n_i. \tag{9}$$

On the demand side, because of (2), one can redefine the demand price functions in terms of product shipments as:

$$\hat{\rho}_k^i = \hat{\rho}_k^i(Q) \equiv \rho_k^i(d), \quad i = 1, \ldots, I; k = 1, \ldots, o. \tag{10}$$

The production cost and the transportation cost functions are assumed to be convex and continuously differentiable and the demand price functions to be monotonically decreasing in demands, and continuously differentiable.

Some Reformulations

We will also replace the labor variables in the firms' objective functions with their product shipment equivalents. Towards that end, in view of (4) and (1), we have that:

$$\frac{\sum_{k=1}^{o} Q^i_{jk}}{\beta^i_j} = l^i_j, \quad i = 1, \ldots, I; j = 1, \ldots, n_i. \tag{11}$$

Also, in view of (5), we have that

$$\frac{Q^i_{jk}}{\beta^i_{jk}} = l^i_{jk}, \quad i = 1, \ldots, I; j = 1, \ldots, n_i; k = 1, \ldots, o. \tag{12}$$

Optimization Problems in Production Shipment Variables

$$\text{Maximize} \quad \hat{U}^i(Q) = \sum_{j=1}^{n_i} \sum_{k=1}^{o} \frac{\hat{\rho}^i_k(Q) Q^i_{jk}}{(1+\tau^i_{jk})} - \sum_{j=1}^{n_i} \hat{f}^i_j(Q) - \sum_{j=1}^{n_i} \sum_{k=1}^{o} \hat{c}^i_{jk}(Q)$$

$$- \sum_{j=1}^{n_i} w^i_j \frac{\sum_{k=1}^{o} Q^i_{jk}}{\beta^i_j} - \sum_{j=1}^{n_i} \sum_{k=1}^{o} w^i_{jk} \frac{Q^i_{jk}}{\beta^i_{jk}} \tag{13}$$

subject to:

$$\frac{\sum_{k=1}^{o} Q^i_{jk}}{\beta^i_j} \leq \bar{l}^i_j, \quad j = 1, \ldots, n_i, \tag{14}$$

$$\frac{Q^i_{jk}}{\beta^i_{jk}} \leq \bar{l}^i_{jk}, \quad j = 1, \ldots, n_i; k = 1, \ldots, o, \tag{15}$$

$$Q^i_{jk} \geq 0, \quad j = 1, \ldots, n_i; k = 1, \ldots, o. \tag{16}$$

Some Preliminaries

The utility functions of all the firms are assumed to be concave and continuously differentiable.

We define the feasible sets:

$$K^i \equiv \{Q^i | Q^i \, \text{satisfies} \, (14) - (16)\}, \quad i = 1, \ldots, I \qquad (17a)$$

and

$$K \equiv \prod_{i=1}^{I} K^i. \qquad (17b)$$

Nash Equilibrium Conditions

Definition 1: Global Supply Chain Network Nash Equilibrium Under Ad Valorem Tariffs

A product shipment pattern $Q^* \in K$ is a global supply chain network Nash Equilibrium under ad valorem tariffs if, for each firm i; $i = 1, \ldots, I$, the following equilibrium condition holds:

$$\hat{U}^i(Q^{i*}, Q^{-i*}) \geq \hat{U}^i(Q^i, Q^{-i*}), \quad \forall Q^i \in K^i, \tag{18}$$

where $Q^{-i*} \equiv (Q^{1*}, \ldots, Q^{i-1*}, Q^{i+1*}, \ldots, Q^{I*})$.

According to (18), a Nash Equilibrium is established if no firm, unilaterally, with its selected strategies, can improve upon its utility, given the strategies of the other firms.

Variational Inequality Formulation

Theorem 1: Variational Inequality Formulation of the Global Supply Chain Network Nash Equilibrium Under Ad Valorem Tariffs

A product shipment pattern $Q^* \in Ki$ is a global supply chain network Nash Equilibrium under ad valorem tariffs according to Definition 1 if and only if it satisfies the variational inequality:

$$-\sum_{i=1}^{I}\sum_{j=1}^{n_i}\sum_{k=1}^{o}\frac{\partial \hat{U}^i(Q^*)}{\partial Q^i_{jk}} \times (Q^i_{jk} - Q^{i*}_{jk}) \geq 0, \quad \forall Q \in K. \tag{19}$$

Alternative Variational Inequality Formulations

Theorem 2: Alternative Variational Inequality Formulations

VI (19) is equivalent to solving: determine $(Q^*, \lambda^*, \mu^*, \epsilon^*) \in R_+^{\sum_{i=1}^{I} n_i o} + R_+^{\sum_{i=1}^{I} n_i} + R_+^{2\sum_{i=1}^{I} n_i o}$ *such that:*

$$\left[-\sum_{i=1}^{I}\sum_{j=1}^{n_i}\sum_{k=1}^{o}\frac{\partial \hat{U}^i(Q^*)}{\partial Q^i_{jk}} + \frac{\lambda^{i*}_j}{\beta^i_j} + \frac{\mu^{i*}_{jk}}{\beta^i_{jk}} - \epsilon^{i*}_{jk}\right] \times \left[Q^i_{jk} - Q^{i*}_{jk}\right]$$

$$+\sum_{i=1}^{I}\sum_{j=1}^{n_i}\left[\bar{l}^i_j - \frac{\sum_{k=1}^{o} Q^{i*}_{jk}}{\beta^i_j}\right] \times \left[\lambda^i_j - \lambda^{i*}_j\right]$$

$$+\sum_{i=1}^{I}\sum_{j=1}^{n_i}\sum_{k=1}^{o}\left[\bar{l}^i_{jk} - \frac{Q^{i*}_{jk}}{\beta^i_{jk}}\right] \times \left[\mu^i_{jk} - \mu^{i*}_{jk}\right] + \sum_{i=1}^{I}\sum_{j=1}^{n_i}\sum_{k=1}^{o} Q^{i*}_{jk} \times \left[\epsilon^i_{jk} - \epsilon^{i*}_{jk}\right] \geq 0,$$

$$\forall (Q, \lambda, \mu, \epsilon) \in R_+^{\sum_{i=1}^{I} n_i o + \sum_{i=1}^{I} n_i + 2\sum_{i=1}^{I} n_i o}. \qquad (20)$$

Alternative Variational Inequality Formulations

Or simplified as: determine $(Q^*, \lambda^*, \mu^*) \in R_+^{2\sum_{i=1}^{I} n_i o} + R_+^{\sum_{i=1}^{I} n_i}$ *such that:*

$$\left[-\sum_{i=1}^{I}\sum_{j=1}^{n_i}\sum_{k=1}^{o}\frac{\partial \hat{U}^i(Q^*)}{\partial Q_{jk}^i} + \frac{\lambda_j^{i*}}{\beta_j^i} + \frac{\mu_{jk}^{i*}}{\beta_{jk}^i}\right] \times \left[Q_{jk}^i - Q_{jk}^{i*}\right]$$

$$+\sum_{i=1}^{I}\sum_{j=1}^{n_i}\left[\bar{I}_j^i - \frac{\sum_{k=1}^{o} Q_{jk}^{i*}}{\beta_j^i}\right] \times \left[\lambda_j^i - \lambda_j^{i*}\right]$$

$$+\sum_{i=1}^{I}\sum_{j=1}^{n_i}\sum_{k=1}^{o}\left[\bar{I}_{jk}^i - \frac{Q_{jk}^{i*}}{\beta_{jk}^i}\right] \times \left[\mu_{jk}^i - \mu_{jk}^{i*}\right] \geq 0,$$

$$\forall (Q, \lambda, \mu) \in R_+^{2\sum_{i=1}^{I} n_i o + \sum_{i=1}^{I} n_i}. \qquad (21)$$

Numerical Examples

Global Soybean Trade Network

- Soybeans are a leading agricultural commodity in global trade, widely used in livestock feed, plant-based foods, and biofuels, with the market valued at USD 169.65 billion in 2024 and projected to reach USD 255.39 billion by 2033.

- Global soybean trade is highly concentrated, with Brazil, the United States, and Argentina as leading exporters and China as the dominant importer, making the market particularly sensitive to tariff policies such as those observed during the 2018 US–China trade conflict.

What Happened to US Soybean Farmers in 2025

- **US soybean purchases by China fell sharply in 2025: after halting imports at the end of May, China resumed buying in November, but purchases totaled only $21.83 million, more than 99% below November 2024 levels.**

- **Tariffs shifted China's soybean imports toward South America, causing billions of dollars in lost sales for US soybean farmers.**

- **The US government announced about $11 billion in Farmer Bridge Payments to support farmers, including soybean producers, affected by temporary trade disruptions and rising production costs.**

- **Increased immigration crackdowns have created significant labor shortages in US agriculture, where about 40% of farmworkers are undocumented.**

Network Topology

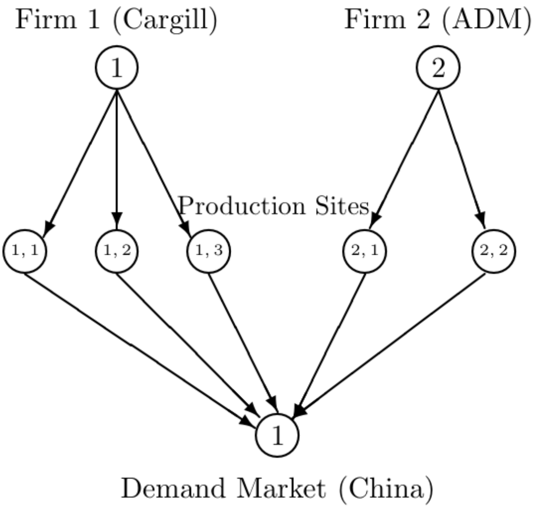


Figure: The Soybean Supply Chain Network Topology for Examples 1, 2, 3, and 4

Example 1: No Ad Valorem Tariffs - Data

• **Two firms representing major US soybean exporters (stylized versions of Cargill and ADM). Firm 1 operates three production sites (US, Brazil, Argentina), while Firm 2 operates two (US, Brazil).**

• **The single demand market represents China, the world's largest soybean importer.**

• **Labor wages differ by country: highest in the US and lower in Brazil and Argentina.**

• **Ad valorem tariffs are zero: $\tau^i_{jk} = 0$.**

• **Labor productivity parameters and upper bounds:**

$$\beta^i_j = 0.7, \forall i, j, \quad \beta^i_{jk} = 0.7, \forall i, j, k,$$

$$\bar{l}^i_{jk} = 3 \times 10^7, \forall i, j, k,$$

$$\bar{l}^1_2 = \bar{l}^2_2 = 3 \times 10^7, \quad \bar{l}^1_1 = \bar{l}^1_3 = \bar{l}^2_1 = 2 \times 10^7.$$

Example 1: No Ad Valorem Tariffs - Functions

Production Costs

$$\hat{f}_1^1(Q) = 10^{-5} {Q_{11}^1}^2 + 90, \quad \hat{f}_2^1(Q) = 4.3 \times 10^{-6} {Q_{21}^1}^2 + 80,$$
$$\hat{f}_3^1(Q) = 7.3 \times 10^{-5} {Q_{31}^1}^2 + 100, \quad \hat{f}_1^2(Q) = 1.8 \times 10^{-5} {Q_{11}^2}^2 + 90,$$
$$\hat{f}_2^2(Q) = 9 \times 10^{-6} {Q_{21}^2}^2 + 80.$$

Transportation Costs

$$\hat{c}_{11}^1(Q) = 2 \times 10^{-5} {Q_{11}^1}^2 + 40, \quad \hat{c}_{21}^1(Q) = 5 \times 10^{-6} {Q_{21}^1}^2 + 30,$$
$$\hat{c}_{31}^1(Q) = 6 \times 10^{-5} {Q_{31}^1}^2 + 45, \quad \hat{c}_{11}^2(Q) = 10^{-5} {Q_{11}^2}^2 + 30,$$
$$\hat{c}_{21}^2(Q) = 4 \times 10^{-6} {Q_{21}^2}^2 + 15.$$

Demand Prices

$$\rho_1^1(d) = -1.8 \times 10^{-5} d_1^1 - 10^{-5} d_1^2 + 950,$$
$$\rho_1^2(d) = -10^{-5} d_1^1 - 2.5 \times 10^{-5} d_1^2 + 1050.$$

Discussion of Results: Example 1

- **Exports from Brazilian production sites exceed those from US sites, consistent with observed global soybean trade patterns and the real-world trade shares of major firms such as Cargill and ADM.**

- **Labor allocation follows production scale, with the largest number of workers employed at Brazilian production sites.**

- **Demand prices in China are $531.16 per ton for Firm 1 and $569.77 per ton for Firm 2, both broadly consistent with observed soybean import price of $463.**

- **Firm 1 earns higher profits due to its larger production scale, and all Lagrange multipliers associated with labor constraints are zero, indicating that no labor constraints bind at equilibrium.**

Example 2: China's Retaliatory Ad Valorem Tariff on US Soybean Exports

• **In Example 2, the data are the same as in Example 1 except that we now examine the impact of a newly imposed 25% ad valorem tariff by China on US soybean imports, announced in April 2025 in direct response to US tariff measures earlier that month.**

• **The supply chain network structure remains as in Example 1, but we incorporate an ad valorem tariff rate on shipments from US production sites of both firms:**

$$\tau^1_{11} = \tau^2_{11} = 0.25.$$

Discussion of Results: Example 2

- **A 25% Chinese tariff rate reduces the competitiveness of US soybean exports, causing shipments from US sites to decline and shifting production toward Brazil and Argentina.**
- **For Firm 1, exports from the US site drop by 22.26%, while shipments from the US site for Firm 2 decline by 20.44%.**
- **Demand prices in China increase slightly as total soybean supply declines, reaching $536.62 and $577.10 per ton for the two firms.**
- **Labor hours fall at US production sites and transportation routes but rises in Brazil and Argentina.**
- **Profits decline for both firms, by 3.64% for Firm 1 and by 5.76% for Firm 2, despite the reallocation of production.**
- **All Lagrange multipliers remain zero in this example.**

Example 3: Immigration Policy and its Impact on Available Labor at the US Production Sites

• **Example 3 has the same data as that in Example 1, except that we now examine the impact of the current farm labor shortage in the US due to increased immigration enforcement.**

• **In 2025, intensified immigration enforcement and the failure to renew working authorizations led to an estimated 70% of the agricultural workforce in key regions, especially California, stopping work.**

• **To simulate the labor shortage, we reduce the available labor hours at both firms' US production sites to $\bar{l}_1^1 = \bar{l}_1^2 = 2 \times 10^6$ hours.**

Discussion of Results: Example 3

- **Reduced labor availability at US production sites significantly disrupts soybean output for both firms.**
- **US shipments decline sharply: by 54.32% for Firm 1 and 59.95% for Firm 2, with labor constraints binding at the US sites.**
- **Positive Lagrange multipliers ($\lambda_1^{1*} = 85.10$, $\lambda_1^{2*} = 108.28$) indicate that the labor upper bounds are binding.**
- **Both firms reallocate production toward Brazil and Argentina, increasing shipments and labor usage at these sites and their associated transportation routes.**
- **Demand declines slightly while demand prices increase to \$545.31 and \$590.51 per ton.**
- **Profits change only modestly due to international production reallocation.**

Example 4: Combined Impact of Ad Valorem Tariffs Imposed on US and Brazilian Drought-Induced Production Cost Increases

- **Example 4 has the same data as Example 1, except we consider two shocks:**
  - **China imposes a 25% ad valorem tariff on US soybean imports:**

$$\tau_{11}^{1} = \tau_{11}^{2} = 0.25.$$

  - **Drought conditions in Brazil increase production costs at Brazilian sites:**

New Production Cost Functions at Brazilian Sites

$$\hat{f}_2^1(Q) = 7 \times 10^{-6}(Q_{21}^1)^2 + 150, \quad \hat{f}_2^2(Q) = 1.3 \times 10^{-5}(Q_{21}^2)^2 + 150.$$

Discussion of Results: Example 4

- **The combined shock of a 25% ad valorem tariff and higher Brazilian production costs reallocates global soybean trade flows.**

- **US exports increase relative to Example 2 but remain below the Example 1 as firms partially shift production back to the US.**

- **Brazilian exports decline by 7% at both firms, due to higher production costs, while Argentine shipments increase by 19.06% relative to Example 1.**

- **Labor allocation follows the same pattern: declining in Brazil, increasing in Argentina, with US labor higher than in Example 2 and lower than Example 1.**

- **Demand prices reach their highest levels, $557.20 and $600.36, while demands and profits fall to their lowest levels.**

- **All Lagrange multipliers remain zero.**

Results - Equilibrium Product Flows and Labor Hours at the Production Sites and Transportation Routes

	Example 1	Example 2	Example 3	Example 4
Q^{1*}_{11}	3,065,167.00	2,382,688.56	1,400,000.00	2,850,274.69
Q^{1*}_{21}	12,268,105.34	12,736,900.30	13,433,546.57	11,332,297.71
Q^{1*}_{31}	863,239.02	896,019.96	944,735.71	1,027,857.05
Q^{2*}_{11}	3,496,410.27	2,781,649.05	1,400,000.00	3,331,122.34
Q^{2*}_{21}	9,234,026.64	9,728,068.38	10,668,295.98	8,570,370.78
l^{1*}_{11}	4,378,810.01	3,403,840.80	2,000,000.00	4,071,820.99
l^{1*}_{21}	17,525,864.77	18,195,571.86	19,190,780.81	16,188,996.73
l^{1*}_{31}	1,233,198.61	1,280,028.51	1,349,622.44	1,468,367.22
l^{2*}_{11}	4,994,871.82	3,973,784.35	2,000,000.00	4,758,746.20
l^{2*}_{21}	13,191,466.63	13,897,240.55	15,240,422.83	12,243,386.84
l^{1*}_{1}	4,378,810.01	3,403,840.80	2,000,000.00	4,071,820.99
l^{1*}_{2}	17,525,864.77	18,195,571.86	19,190,780.81	16,188,996.73
l^{1*}_{3}	1,233,198.61	1,280,028.51	1,349,622.44	1,468,367.22
l^{2*}_{1}	4,994,871.82	3,973,784.35	2,000,000.00	4,758,746.20
l^{2*}_{2}	13,191,466.63	13,897,240.55	15,240,422.83	12,243,386.84

Results - Demand Prices, Demands, and Profits

	Example 1	Example 2	Example 3	Example 4
d_1^{1*}	16,196,511.37	16,015,608.82	15,778,282.28	15,210,429.45
d_1^{2*}	12,730,436.91	12,509,717.43	12,068,295.98	11,901,493.13
$\hat{\rho}_1^1$	531.16	536.62	545.31	557.20
$\hat{\rho}_1^2$	569.77	577.10	590.51	600.36
$\hat{U}^1$	6,502,623,987.76	6,265,508,717.39	6,507,263,407.57	5,933,698,880.38
$\hat{U}^2$	5,502,368,550.04	5,185,244,846.39	5,392,080,170.32	4,902,279,307.20

Insights and Summary

Insights

• **Ad valorem tariffs shift production and trade flows toward sources without tariffs, alter labor allocation at production sites and along transportation routes, and increase demand prices for consumers.**

• **Labor constraints, whether from shortages or immigration policy restrictions, reduce product flows and profitability for the affected firms while creating competitive advantages for less constrained producers.**

• **When ad valorem tariffs and increased production cost disruptions occur together, their effects compound, leading to reduced trade flows, higher demand prices, and lower overall profits.**

• **For policymakers: ad valorem tariffs not only influence prices and trade flows but also interact with labor in shaping competitive outcomes and may reduce total output when implemented widely.**

• **For firms: the results highlight the advantage of diversifying production locations to mitigate the effects of ad valorem tariffs and labor disruptions.**

Summary

• We developed an oligopolistic global supply chain network model that explicitly incorporates ad valorem tariffs and labor constraints, with firms competing noncooperatively across multiple production sites and demand markets.

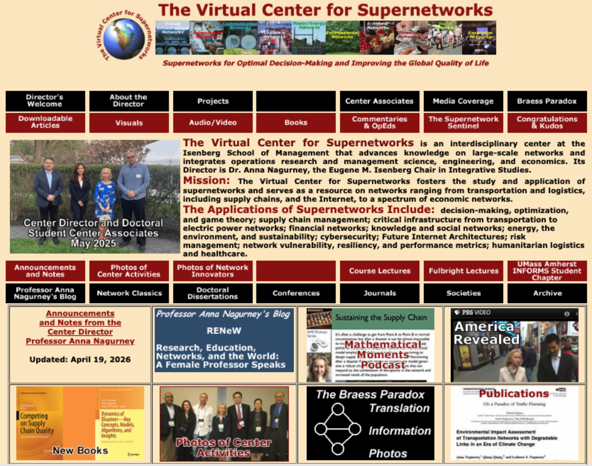
• Labor is modeled as a decision variable at production sites and along transportation routes, subject to site- and route-specific upper bounds, with location-varying wages and productivity factors.

• The governing Nash equilibrium conditions are formulated as a variational inequality; a Lagrange analysis yields an alternative formulation with closed-form iterates suitable for large-scale computation.

• A case study on the global soybean trade examines four scenarios: no tariffs, retaliatory Chinese ad valorem tariffs, US immigration-driven labor shortages, and combined ad valorem tariff and drought shocks.

• Future research directions include incorporating minimum wages, product quality as a decision variable, multitiered supply chain networks, and alternative production cost specifications.

Thank You Very Much!



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