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Posted Date: 9 April 2025

doi: 10.20944/preprints202504.0753.v1

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Crisis-Proofing the Fresh: A Multi-Risk Management Approach for Sustainable Produce Trade Flows

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Abstract: The study posits the need for a conceptual multi-risk management approach for fresh produce, an essential product category for societal resilience, and one constantly affected by climate change, policy volatility, and geopolitical disruptions. The research starts from a literature-informed risk typological mapping, leading to Gephi visualizations of networks related to this trade. Network analysis using 2024 bilateral trade data reveals a core-periphery topology, with the United States, Spain, and the Netherlands as central hubs. A gravity-based simulation model is, lastly, used to address the question: what structural vulnerabilities and flow-based sensitivities define the global fresh produce trade, and how do they respond to simulated multi-risk disruptions? The model uses the case of USA as a global trade hub and induces two compounding risks: a protectionist tariff policy shock and a climate-related shock in its main supplier. The conclusion is that the fragility in the fresh produce trade enhances the cascading effects that any risk event may have across environmental, economic, and social sustainability dimensions. The paper emphasizes the need for anticipatory governance, diversification of trade partners, and investment in cold chain resilience, offering an image for policymakers to acknowledge the risk and mitigate this increasingly fragile fresh produce trade.

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1. Introduction

Before being able to become hunters, humans were gatherers, so fresh produce is an intrinsic part of human evolution and a staple for diet for millennia. Even in modern times, its role remains foundational to human health and nutritional well-being. And yet, more than "1.7 million deaths worldwide are being attributed to low fruit and vegetable consumption" [1]. Fresh produce, defined as "fresh fruits and vegetables […] that is likely to be sold to consumers in an unprocessed or minimally processed (i.e., raw) form" [2], is essential for global health, nutritional security and central to achieving **Sustainable Development Goals: SDG 2** (Zero Hunger) and **SDG 3** (Good Health and Well-being).

It is also a significant part of the international agri-food trade, with the revenue in 2025 amounting to 1,653.56 billion USD (875.19 billion USD from fresh vegetables and 778.37 billion USD from fresh fruit) [3,4]. Both markets are expected to grow annually by more than 6% (CAGR 2025-2030 for vegetables – 6.68% and for fruits – 6.28%) [3,4]. This significant growth is supported by complex supply chains that enable year-round and worldwide access to products that are seasonal and regional.

However, fresh produce is perishable, with short shelf life, temperature and other sanitary and phytosanitary (SPS) sensitivity, and seasonal availability. Thus, its logistics are complex and specific and require specialized infrastructure—most notably cold chain systems and rapid distribution networks. These characteristics distinguish it from other commodities, but they also increase the vulnerability of its supply chain to local as well as systemic disruptions. Of particular importance is

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the fact that, unlike cereals or processed foods, fresh produce depends on cold chains and, thus, has little buffer time, which means its trade is more exposed to even minor delays or disruptions.

At the same time, the structure of the global trade in produce is growing in complexity. Studies from the past decade mention that it displays scale-free and small-world topologies [5,6], concentrating flows amongst several hubs, such as the USA, Netherlands, or China. Among these hubs, the USA stands out as a major consumer market equivalent to a gravitational centre, a status quo that increases the systemic stakes of any unilateral disruption originating there.

Still, there is also a growing role for intermediary countries that may redistribute flows across trade corridors to enhance connectivity [7]. These additions increase, however, the network complexity, which may become more efficient but also increase the risks associated and create fragility. This is also due to the fact that chokepoints and central nodes can propagate shocks rapidly across the network and expose downstream actors to cascading effects [7–9]. Although the perception of risk events as siloed is easier to handle, particularly in research, the interconnection of risks (as also considered by the World Economic Forum in its yearly Global Risks Reports) is evermore relevant, as the result is often non-linear amplification, generating disruptions that exceed the sum of their parts.

The fragility of the structure adds to the fragility of the produce, affected mainly by climate change, water availability, and increased postharvest spoilage [10]. But there are other types of risks to take into consideration, from crop diseases to price surges due to export bans or tariffs, to nutrient loss, to geopolitical tensions (such as the war in Ukraine) impacting trade and exposing import-reliant regions like Sub-Saharan Africa to critical supply shocks. All these disruptions, many as they may be, are exacerbated by the scale-free, core-periphery nature of global fresh produce networks, in which just a few central hubs handle disproportionately high volumes of trade. Most analytical models isolate these risks, focusing only on one at a time, and often fail to capture their compound effects and flow-sensitive risks, which are so relevant for this type of commodity.

Although the literature on the topic is numerous and growing, most studies focus either on cereals (wheat and maize) or food in general and predominantly employ single-risk modeling [9,11,12]. Very few analyses provide integrated multi-risk models, and even less so based on fresh produce, which highlights a lack of hybrid modeling frameworks that integrate trade flow forecasting (via gravity models) with network-based mapping of structural and dynamic vulnerabilities for this particular type of commodity.

In this context, this paper comes to fill this literature gap by proposing a hybrid model meant to answer this research question

"Using a hybrid approach (integrating various methodologies), what structural vulnerabilities and flow-based sensitivities define the global fresh produce trade, and how do they respond to simulated multi-risk disruptions, including climate volatility and policy shocks?"

The model will, thus, (a) map structural vulnerabilities in the global fresh produce trade, (b) analyze flow-based sensitivities under compound, systemic shocks, and (c) simulate responses to multi-risk scenarios.

In theory, this study advances trade modeling by linking it to a risk assessment that econometrically captures both structural and dynamic dimensions of trade risk. Empirically, the study provides a perspective on fresh produce, which, in turn, may equip policymakers with insights relevant to potential mitigations to country-specific risks, enhancements of food system resilience, and/or trade diversification. If the food system resilience is often referred to logistical terms, in this study, we consider it from a broader sustainability perspective – environmental (waste and spillage), social (access to nutritious food), and economic (cost and market stability). To conclude, the study integrates typological, network-based, and econometric perspectives to assess structural and dynamic vulnerabilities in the global fresh produce trade system, framing them as potentially eroding factors for the aforementioned sustainability.

To address the central research question, the paper is structured in a linear manner, from Section 2 presenting the hybrid model methodology and data sources, to Section 3 reviewing the relevant

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literature to inform a typological risk mapping, Section 4 detailing the results of the hybrid model and, lastly, Section 5 concluding the study including sustainability, resilience and governance implications and directions for future work.

2. Materials and Methods

As the search term "fresh produce trade vulnerability" yields more than 338,000 results on Google Scholar (as of March 2025), and "fresh produce trade network vulnerability" returns roughly 226,000, of which 14,700 in the last 5 years, a multirrisk framework requires both systematic search, screening protocol and multiple methodologies to ensure both methodological rigor and comprehensive coverage.

In this view, this study uses a three-pronged approach to capture the unique structural and flow-based vulnerabilities of the global fresh produce trade system: by integrating (a) typological risk mapping of structural vulnerabilities, (b) network analysis of trade structure and flow sensitivities, and (c) a gravity-based trade simulation model under multi-risk disruption scenarios. This triangulated approach ensures the proper (both descriptive and predictive) identification of systemic chokepoints, a suitable quantification of flow sensitivity, and the ability to simulate the potential impacts of compounding events, leading to a clearer image of how trade shocks may reverberate through the global fresh produce system.

The first step is a **literature-informed typological risk mapping**. The method is used increasingly in research pertaining to agri-food systems due to its ability to enhance the interpretability of network-based models see studies using similar methodological approaches in [13–17]. This step consists of a systematic review of literature on the topic, from which relevant disruptions were extracted and coded for the global food network and, more specifically, for the fresh produce trade. The resulting typology is not an end in itself. This step acts as a filter for identifying relevant compound risks to be modeled and tested in the simulation layer.

By referring to previous work [9], we grouped risks into three categories:

- **Climate-related risks** (e.g., heat stress, water scarcity, post-harvest spoilage)
- **Policy shocks** (e.g., export bans, SPS restrictions, tariff volatility)
- **Geopolitical disruptions** (e.g., conflict-induced route closures, trade embargoes).

To create a risk typology matrix, these risks were cross-tabulated against known sensitivity indicators, such as import dependence, supply concentration, perishability, and cold chain reliance, to synthesize multi-risk exposure. The matrix builds upon a methodology from cyber security – the vulnerability prioritization framework [18].

The second step is focused on identifying the structural topology of the global fresh produce trade and uses **a network** based on 2024 bilateral trade data from UN Comtrade, using HS-4 level product codes corresponding to fresh fruit and vegetable categories. Nodes represent countries; edges represent trade volumes in USD. The network is visualized with Gephi, and applies specific filtering methods and algorithms to identify core–periphery structures. The hypothesis is that, consistent with the literature ([6,8]), the network will exhibit scale-free and small-world properties. The method is widely used in the identification of agri-food trade vulnerabilities [19,20]. The aim of this step is not to run a formal network simulation but to understand how the architecture of trade, particularly the structural centrality of major trade hubs, sets the stage for vulnerability, especially in a multi-risk context (paired with a permacrisis background).

The third step is a gravity model of trade flows meant to assess the flow-based sensitivity of global fresh produce trade. It is of particular importance for this step to stress that fresh produce markets, due to their perishability and trade concentration, are particularly sensitive to cost changes.

To stress-test the network, we use a scenario based on a single exogenous policy shock which evaluates the ripple effects of a major policy intervention by a central actor, more specifically, a 10% across-the-board tariff imposed by the United States of America on all fresh produce imports, increased to 25% for shipments from Mexico and Canada. The scenario is based on the real baseline

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tariff imposed by President Donald Trump on April 2nd, 2025, and it encapsulates both a plausible geopolitical and a protectionist policy shock with global systemic ramifications, mainly due to the central role of the country in the global produce flows. This central role has already been indicated by the two previous steps. This trade shock (which builds on the work of [21] based on the measures from the first Trump administration) is treated both as a standalone disruption and in a compound scenario alongside climate-related production losses. The simulation uses a modified gravity model, with trade volume responses estimated using elasticity values ([21]), treated as heuristic parameters, not calibration outputs. The

For this, we estimate a basic log-linear gravity model with the following equation:

$$\ln(T\_iUS) = b0 + b1*\ln(GDP\_i) + b2*\ln(Distance\_iUS) + b3*Border\_iUS + b4*Tariff\_iUS + b5*SPS\_iUS + e\_iUS \quad (1)$$

Where:

- T_iUS: Value of fresh produce exports from country *i* to the United States. Data source: UN Comtrade (HS 07–08, USA imports only);

- GDP_i: Gross Domestic Product of exporter. Data source: World Bank WDI;

- Distance_iUS: Geographic distance between country *i* and USA. Data source: CEPII GeoDist (to U.S. only);

- Border_iUS: Dummy variable indicating shared border. Manual: 1 for Mexico, Canada; 0 otherwise;

- Tariff_iUS: Applied ad valorem tariff rate on fresh produce exports from country *i* to US. Data source: MacMap (to U.S. by HS6);

- SPS_iUS: Dummy variable for the presence of non-tariff SPS measures that constrain trade in perishables (1 = SPS restriction in place; 0 = otherwise). Data source: WTO SPS IMS database;

- b1-b5: Estimated coefficients;

- e_iUS: Error term.

The data is collected for 2024 to eliminate the shock effects of the pandemic and the war in Ukraine, both extremely significant in the agrifood trade as exhibited by literature. The simulation for the 10% across-the-board tariff for the United States uses the following method:

- We assume baseline trade values – as predicted from the gravity model
- We assume the elasticity of trade to tariff shocks as -0.95 [21]. (the detailed reason the value is explained in the Results section). (Baseline elasticity values used range from -0.8 to -1.2, depending on the commodity and source country, with demand-side price sensitivity assumed to remain constant across scenarios.)
- The model outputs a predicted reduction in trade volumes and identifies the most affected exporters.
- We presume no retaliatory measures from the exporters.
- We revise trade flows following this equation:

$$T\hat{}\_\{iUS\}\hat{}\{tariff\} = T\_\{iUS\}\hat{}\{baseline\} \times (1 + \Delta\tau\_\{iUS\})\hat{}\varepsilon, \quad (2)$$

Where:

- T̂_{iUS}^{tariff} is the adjusted trade volume after the tariff shock;
- T_{iUS}^{baseline} is the predicted trade flow from the gravity model (from equation (1));
- Δτ_{iUS} is the change in tariff rate (e.g., from 0% to 10% or 25%);
- ε is the price elasticity of trade (e.g., -0.95).

 doi:10.20944/preprints202504.0753.v1

The reason for choosing this third step of the methodology resides in the fact that gravity models are a traditional method in policy analysis and have proven effective in modeling tariff effects ([22]). Moreover, the scenario design allows for basic sensitivity testing and shows if trade volumes decline linearly or exponentially under dual stress conditions.

Lastly, building on these three steps, we link in the final analytical layer these potential shocks to sustainability impacts across three dimensions: (a) environmental (e.g., increased emissions and food waste); (b) economic (e.g., price volatility, supply instability); and (c) social (e.g., reduced access to affordable, nutritious food). These impacts are qualitatively assessed and, where applicable, supported by secondary data estimates, in view of highlighting where systemic shocks may erode long-term sustainability in disproportionate ways.

3. Understanding Fresh Produce Trade Networks: A Critical Literature Review

To properly identify relevant disruptions and classify them in a way that supports both network interpretation and simulation design, we use the typological risk mapping method used in agri-food systems research, as previously mentioned.

For this, we retrieved between February and March 2025 a set of 500 articles and expert reports from various databases (Scopus, Semantic Scholar and other sources: FAO, WTO, USDA) through hybrid keyword strings (e.g., "fresh produce trade AND network analysis", "gravity model AND agricultural shocks", "food trade resilience AND climate change"), starting from the research question. We included studies based on relevance to international fresh produce trade, application of gravity or network models, and coverage of climate, policy, or geopolitical disruptions and excluded those focused solely on domestic trade or non-agricultural commodities, and the screening questions, taken holistically, were the following:

- Does the study analyze international (rather than purely domestic) trade networks of agricultural products or fresh produce?
- Is the primary focus on agricultural/fresh produce supply chains?
- Does it include analysis of fresh/unprocessed agricultural products?
- Does it employ gravity models and/or network analysis methods with the potential for integrated analysis?
- Does it include quantitative analysis rather than purely descriptive analysis?
- Does it refer to at least one of the following risks: climate change, trade policy, or geopolitical events?

The final selection of 150 papers related to global food trade issues and 40 related to fresh produce trade covers various methodological approaches and includes both theoretical and empirical contributions, mapping the state of the art and highlighting critical gaps motivating the hybrid gravity-network model proposed in this paper. Only those studies explicitly referenced in the paper were included in the list of references, and the list of revised supplementary papers is found in Appendix A.

Based on the entire corpus of 150 papers on global food trade networks, we identify three thematic clusters: (1) structural vulnerabilities in global produce networks, (2) flow-based sensitivities to systemic risk, and (3) adaptive capacities and resilience mechanisms, moving a linear way from why some countries and flows are at risk to how disruptions impact them to what can be done about it. A conceptual synthesis of these clusters is presented in Figure 1. While they emerge from the broader literature on global food trade networks, they are still relevant for fresh produce, given its sensitivity to disruption and dependence on concentrated trade flows. Basically, we infer that fresh produce networks are more fragile versions of the larger global food trade systems.

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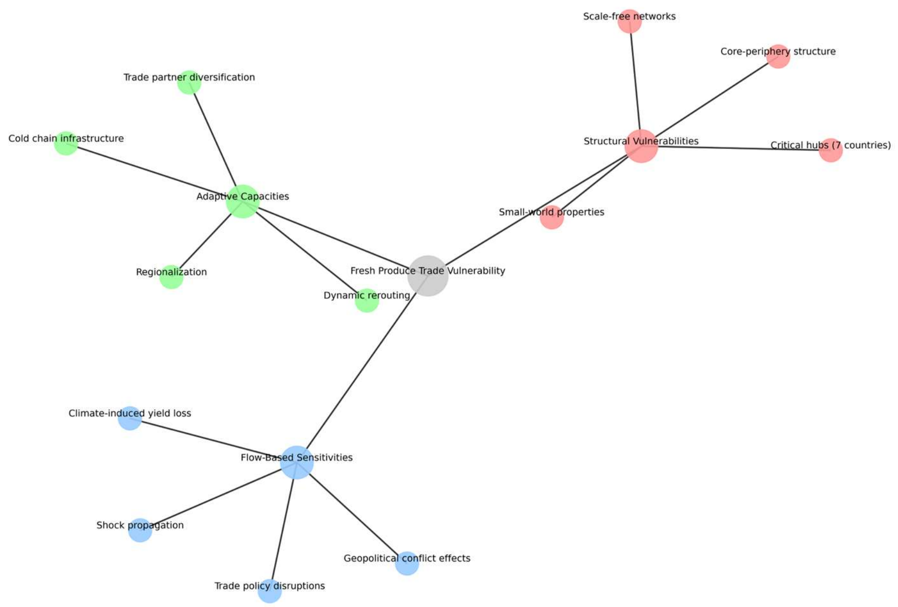

Figure 1. Adapted conceptual clusters from global food trade literature, applied to fresh produce.

The first thematic cluster refers to the structural risks related to the global food and fresh produce trade networks, more specifically derived from their core-periphery topology. A detailed insight mapping may be found in Tables 1 and 2. The findings reflect that in the landscape of this particular commodity, a few central exporters act as systemic hubs, and the numerous rest function as peripheral, import-reliant nations. Seven entities (countries and supranational economic unions) form the core of the International Food Trade Network. They collectively engage with over 77% of global trade partners and account for nearly a third of the trade volume [6], a status quo that has held for more than a decade.

Table 1. Structural Vulnerabilities in *Global Food Trade Networks*

Structural element	Empirical Evidence / Metrics	Key Interpretation	Implications for Vulnerability	Referenced Key Studies
Core-periphery structure	7 countries (USA, EU, China, India, Brazil, Russia, Japan) manage >77% of all trade links; ~30% of global flux	Trade is concentrated in a few global hubs	Shock in one core node affects global system	[6,8,23–25]
Network topology	Scale-free, small-world networks with high clustering; average path length L ≈ 1.52	Efficient under normal conditions, vulnerable to cascading failures	Fast propagation of risk due to short paths	[20,25–27]
Modularity & clustering	Regional modularity: Europe ~0.49 stability, Africa lower	Clustering enhances regional resilience but can also isolate	Weak communities = higher regional sensitivity	[28–33]
Critical nodes (centrality)	High betweenness/PageRank: Netherlands,	Key actors act as bridges—failure leads to major disruption	Systemic chokepoints elevate fragility	[34–37]

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	Ukraine, USA, China are key			
Import dependency (periphery)	Sub-Saharan Africa, MENA show low connectivity and high import reliance	Peripheral zones face exposure from few redundant sources	High exposure to price and supply shocks	[11,33,38–40]
Commodity-specific flow vulnerability	Vulnerability varies by product: wheat, grains, magnesium-rich products are high-risk	Certain commodities are more prone to risk from single-point failures	Risk varies by trade structure of each crop	[20,41–44]

These hub-and-spoke networks exhibit scale-free and small-world properties, meant to enhance efficiency (provided the conditions are stable) with short average path lengths, high clustering, and power-law distributions of trade flow [20]. The same characteristics also become risk factors and intensify fragility under systemic stress. This fragility may be quantified by using network metrics, such as network density (which [32] find to reflect limited redundancy), clustering coefficients (moderate, as per [32]) or chokepoints and exposure pathways [31]. These metrics may also inform sub-national and regional insights, such as the case of identifying bridging countries that connect modular trade regions [34]. Along the same line, studies also highlight that community clustering can either buffer or amplify shocks, depending on the geographic configuration and the commodity in question [29].

The core-periphery topology as a structural vulnerability is based on asymmetric dependencies between exporting and importing countries. Regions such as Sub-Saharan Africa and the Middle East rely heavily on a narrow set of suppliers, having an increased sensitivity to even modest trade flow perturbations ([43] and [11]). This systemic exposure has intensified with the pandemic-era trade dynamics [25]. It is to be noted that both these regions are also affected by significant geopolitical risks not directly related to food networks, and hence, this (latent) risk factor may rapidly trigger cascading failures under compound disruptions.

Even if the referenced studies refer to the entire food network, the structural traits keep for fresh produce with a certain number of distinctive vulnerabilities being applied solely to them. These are mapped in Table 2. They start from the foundational works of [45] and [46], who model the effects of spoilage and inventory decay and show that perishability is a systemic constraint on trade flow flexibility. [47] show that fresh produce is more infrastructure-dependent than most dry goods by simulating logistics networks where temperature control and cold chain reliability are essential for system resilience. Adding to the landscape are regional trade agreements (such as NAFTA or the Chinese-Myanmar melon link) that shape the topology and path-dependence of produce exports, in a linkage of structural trade flows to regulatory frameworks [48]. Lastly, works such as [49] show that regions like the U.S. Southwest are structurally exposed due to water-intensive production under climatic stress, highlighting the position of fresh produce within the broader Food-Energy-Water (FEW) nexus.

Table 2. Structural Vulnerabilities in Global **Fresh Produce** Trade Networks

Structural element	Empirical Evidence / Metrics	Key Interpretation	Implications for Vulnerability	Referenced Key Studies
Cold chain dependency	Cold chain failures account for up to 30% postharvest losses in perishables (especially fruits and leafy greens).	High reliance on temperature-controlled logistics.	Breakdowns cause large-scale spoilage and supply loss.	[50–52]

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Postharvest decay & perishability	Spoilage rates are exponentially time-sensitive; up to 40% loss within 3–5 days if not refrigerated or delayed in transit.	Perishability acts as a hard constraint on trade flexibility.	Supply chain rigidities amplify effects of shocks.	[45,46,51]
Climate exposure in yield zones	Berry and lettuce production show strong correlation with climate volatility. Yield drops by 10–15% under high-heat or drought conditions.	Climate-sensitive crops cluster in vulnerable geographies.	Climate volatility disrupts both production and flow stability.	[49,53]
Regional trade dependencies	The U.S. imports ~70% of fresh vegetables from Mexico and 25% of fresh fruit from Mexico and Chile.	Highly asymmetric dependency on a few partners.	Exposure to bilateral shocks and seasonal bottlenecks.	[54,55]
Seasonality and NAFTA corridors	Fresh produce trade shows seasonal surges tied to trade agreements like NAFTA. Regulatory shifts cause disproportionate seasonal impact.	Seasonality and path dependency increase systemic sensitivity.	Disruptions coincide with peak demand, increasing systemic fragility.	[48,52,53]
Homogenization of supply sources	Export concentration in a few hubs (e.g., Mexico, Chile) has intensified since 2000, especially in off-season produce like berries, peppers, and tomatoes.	Trade centralization reduces adaptive capacity.	Risk of synchronized disruption and limited substitution options.	[49,50,55]

In a nutshell, similarly to the global food network, the fresh produce supply chain is fragilized by unbalanced supply and demand, transport bottlenecks, and seasonal cycles [56]. Certain countries, although hubs, rely heavily on imports for certain produce (for instance, China and soybeans), thus becoming vulnerable to trade disruptions like tariffs and other types of trade frictions and policy changes [28,57,58]. Lastly, the governance structure of the value chain in some regions (see the Myanmar-China melon trade in which brokers control the chain instead of retailers [48]) significantly affects the risk-reward distribution and may possibly inhibit upgrades, technological innovation, and, consequently, increase risk.

If the first thematic cluster allows for the identification of high-risk nodes and flows, which are further assessed in the network modeling phase of the hybrid framework, the second thematic cluster refers to the link of flow-based sensitivities to systemic risk. The former refers to how external shocks, such as climate events, geopolitical instability, or policy shifts, affect the movement of fresh produce across global supply chains. A detailed insight mapping may be found in Table 3.

Table 3. Flow-based Sensitivities in **Fresh Produce** Trade Networks

Flow sensitivity element	Empirical Evidence / Metrics	Key Interpretation	Implications for Vulnerability	Referenced Key Studies
Climate-induced yield loss	Heatwaves/droughts cause 10–25% yield loss in fresh vegetables and berries (US, China, Senegal)	Yield zones are climate-sensitive	Exposure to production shocks increases volatility	[49,59–61]
Trade policy disruptions	Brexit, AfCFTA, and COVID-19 led to up to 30% trade flow reduction in short term	Trade highly responsive to policy shocks	Sudden regulatory shifts amplify fragility	[59,61–63]

Shock propagation	Simulated dual-disruption scenarios (e.g., tariffs + climate) cause non-linear trade flow collapse	Shocks ripple through key corridors	Compounding risks generate systemic volatility	[64–67]
Geopolitical conflict effects	Russia–Ukraine war impacted EU & MENA imports of tomatoes, apples, cucumbers	Conflict-induced rerouting slows trade	Limited alternative corridors for perishable products	[40,63,68]
Transport bottlenecks	Fresh produce logistics disrupted by COVID-19 port closures and labor shortages	Cold chain logistics are rigid and time-sensitive	Delays result in spoilage, loss, and instability	[69–72]
Dual-channel and rerouting limits	Simulation shows constrained ability to shift between retail and wholesale or between corridors (esp. China, India, Egypt)	Path-dependence limits rerouting	Exposure remains high under constrained substitution	[65,73–75]
Seasonal asymmetry	Seasonal peaks in NAFTA corridors amplify stress during disruptions	Certain months carry disproportionate trade load	Higher vulnerability during high season (e.g., winter citrus imports)	[48,76,77]
Yield risk and water scarcity	High water footprint for citrus, berries; global sourcing not aligned with water resilience	Trade patterns may ignore environmental limits	Supply zones collapse under water stress	[60,76,78]
Demand stochasticity	Dynamic modeling shows unpredictable retail demand during COVID-19 and political shocks	Unstable demand increases stress on inventory & logistics	Higher stockouts and excess spoilage risk	[69,70,73]

In literature, the most interest is given to climate change and how climate-induced yield loss poses a major disruption risk for fresh vegetables and fruits. This is mainly true for vulnerable production zones like the U.S. Southwest, Northern China, and parts of Sub-Saharan Africa [59,60]. The second largest impact comes from trade policy disruptions (for instance, Brexit or the emergence of other trade regimes, like AfCFTA) [61,62], which cause reductions in flow volumes up to 30%, hence highlighting the high sensitivity of fresh produce trade to regulatory volatility. This is the main reason why the simulation scenario we test the network on is a compound of both these risks. Particular attention must be given to the importance of shock propagation, beyond isolated shocks, to the non-linear cascading impact of dual disruptions (such as climate change + tariffs), evermore so for time-sensitive perishables [64,65].

Other elements mentioned in the literature talk about the geopolitical conflicts (such as the Ukraine war) in connection to transport bottlenecks and limited dual-channel flexibility as risk amplifiers, and the lack of mitigation measures such as rerouting alternatives due to rigid logistics [40] or substitution which is less agile for non-perishable commodities [69,70]. Another additional significant trigger linked to adaptive innovation is the COVID-19 pandemic ([69,72,74]). Lastly, other underlying environmental constraints (such as water stress, which arguably may be lumped up under the larger climate change risks), demand stochasticity, or seasonal factors contribute to systemic fragility ([48,60,74,76]).

The third and last thematic cluster refers to the adaptive capacity of fresh produce networks. If previous elements referred to why some countries (or flows) are at risk and how disruptions impact them, this last part talks about what can be done about it by mapping the strategic responses and

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resilience-enhancing mechanisms identified in the literature on fresh produce trade. Five main levers are identified, with four others as secondary mitigation mechanisms: cold chain infrastructure, trade partner diversification, regionalization, dynamic rerouting, and overall system responsiveness. As in the case of interconnected risks, these "solutions" are often discussed in conjunction as interdependent elements that may help reduce sensitivity to disruptions. An example in this respect comes from the robustness of the cold chain, which is a prerequisite for rerouting as a mitigation measure ([51,52]) but which also hinges on the logistical and contractual flexibility of suppliers ([61,66]). Another potential mitigator is regionalization, by shifting trade dependency to neighbors (geographically proximate) ([49,57,60]). This is yet another reason to test the resulting framework for the USA case, as it functioned under more or less this logic, however decides to go against the flow and tax its neighbors more. The mapped insights for this thematic cluster are presented in Table 4, which shows a structured synthesis of resilience-building in perishable commodity systems.

Table 4. Adaptive capacity in **Fresh Produce** Trade Networks

Adaptive element	Empirical Evidence / Metrics	Key Interpretation	Implications for Vulnerability	Referenced Key Studies
Cold chain infrastructure	Cold chain failures linked to 30–40% losses in fruits/vegetables	Temperature-sensitive goods need controlled logistics to avoid spoilage	Breakdowns in temperature control systems result in massive loss	[51,76]
Trade partner diversification	Higher diversification reduces supply volatility	Diverse partners reduce overreliance and create fallback options	Low diversity raises exposure to targeted or regional risks	[56,60]
Dynamic rerouting capability	Simulation models show rerouting shortens restoration times	Flexible networks can redirect flows to adapt under disruption	Rigid networks increase downtime post-shock	[61,64,72]
Technology-based real-time tracking	IoT/logistics tech enhances visibility, prevents mismatch	Digital systems allow for agile decision-making	Blind spots in the supply chain delay mitigation	[71,79]
Resilience-oriented regulation	FAO & EU food safety compliance enhance reliability	Strong standards prevent large-scale quality failures in crises	Lack of standards exposes to regulatory and quality shocks	[50,80]
Redundant sourcing & stock buffering	Dual sourcing and buffer stocks dampen ripple effects	Redundancy spreads risk across multiple suppliers	Overconcentration increases system fragility	[66,73]
Market-based price/quality stabilization	Quality-price mechanisms ensure flexible coordination in disruptions	Market design incentivizes adaptive supply behavior	Volatile prices without buffers reduce long-term reliability	[65,74]
Regionalization of supply chains	COVID-19 case studies on regional chains in Senegal	Local/regional networks insulate from global shocks	Over-globalization weakens adaptation to local stressors	[59,81]
Public-private resilience coordination	Multi-agent systems improve preparedness under compound risks	Institutional collaboration improves governance and early response	Weak coordination leads to fragmented responses	[82]

The three clusters were analyzed often through diverse methodologies, but often in a siloed manner, either by referring to a geographical area, to a type of constraint, or to a certain research method. However, there are also studies that adddress them in a more holistic manner. For instance, [83] develop a synthetic modeling framework to simulate commodity flows under compound stress scenarios and link, albeit with limited empirical validation, structural bottlenecks to systemic disruptions. Similarly, [84] propose a multi-objective optimization model that captures the trade-offs between environmental constraints and food availability, which is limited by its theoretical framing to data-constrained contexts. The adaptive capacity (mentioned in thematic cluster 3) may be advanced by technological implementation with, for example, AI-based risk prediction tools tailored to green logistics ([85]), but its effects are still to be proven by reality. Similarly, institutional arrangements and smallholder configurations are proven, albeit qualitatively, by [86] to shape both systemic fragility and adaptive potential and, thus, contribute to thematic clusters 1 and 3. Finally, thematic cluster 2 is enhanced by the work of [87] who highlight the compounding effect of social and environmental risks in China. Our study comes to enrich this landscape of interconnectedness and provide a multi-risk view of the plethora of complexly linked pain points described before.

The thematic clusters were foundational work for the creation of a risk typology map, for filtering relevant compound risks to be modeled and tested in the simulation layer. By referring to previous work [9], we grouped risks into three categories:

- **Climate-related risks** (e.g., heat stress, water scarcity, post-harvest spoilage)
- **Policy shocks** (e.g., export bans, SPS restrictions, tariff volatility)
- **Geopolitical disruptions** (e.g., conflict-induced route closures, trade embargoes).

We cross-tabulate them against several sensitivity indicators, as follows:

- Four core indicators: import dependence, supply concentration, perishability, and cold chain reliance;
- Five additional indicators (relevant for the case chosen to stress-test the framework – USA): regulatory exposure ([48,50,53]), contamination sensitivity ([2,47,48]), labor fragility ([49,69,72]), demand volatility ([48,54,59]) and transport system reliance ([47,49,54]).

The resulting risk typology matrix, using a simplified version of the vulnerability prioritization framework [18], is detailed in Table 5 and visually represented in Figure 2.

Table 5. Risk Typology Matrix: **Fresh Produce** Trade

Sensitivity Indicator	Climate-Related Risks	Policy Shocks	Geopolitical Disruptions
Import Dependence (ID)	**High** (esp. in arid & tropical zones)	**High** (for countries with low food self-sufficiency)	**High** (e.g., landlocked and import-reliant countries)
Supply Concentration (SC)	**Medium–High** (where climate-vulnerable regions dominate exports)	**High** (esp. where few suppliers dominate)	**High** (e.g., those dependent on specific corridors)
Perishability (P)	**Very High** (fresh produce highly sensitive to temperature, water)	**Medium** (disruption timing impacts shelf life)	**Medium** (spoiled if rerouting is slow)
Cold Chain Reliance (CC)	**Very High** (requires refrigerated transport & storage)	**Medium** (custom delays increase spoilage)	**High** (alternative routes often lack cold chain infrastructure)
Regulatory Exposure (RE)	**Medium** (climate-driven SPS barriers increasing)	**Very High** (susceptible to export bans, border protocols)	**High** (rapid shifts in border governance or embargoes)
Contamination Sensitivity (CS)	**High** (heat, water scarcity linked to contamination risk)	**High** (e.g., rejection from stricter SPS inspections)	**Medium–High** (poor handling in rerouting corridors)
Labor Fragility (LF)	**Medium** (heat waves affect farm labor productivity)	**Medium–High** (labor policy impacts trade flows)	**High** (conflict zones or migrant labor routes)
Demand Volatility (DV)	**Medium** (climate events affect consumer behavior)	**High** (price swings due to policy uncertainty)	**High** (supply interruptions drive demand spikes)
Transport System Reliance (TSR)	**High** (infrastructure failure under climate extremes)	**High** (border delays, inspection lags)	**Very High** (blockades, port closures, rerouting needs)

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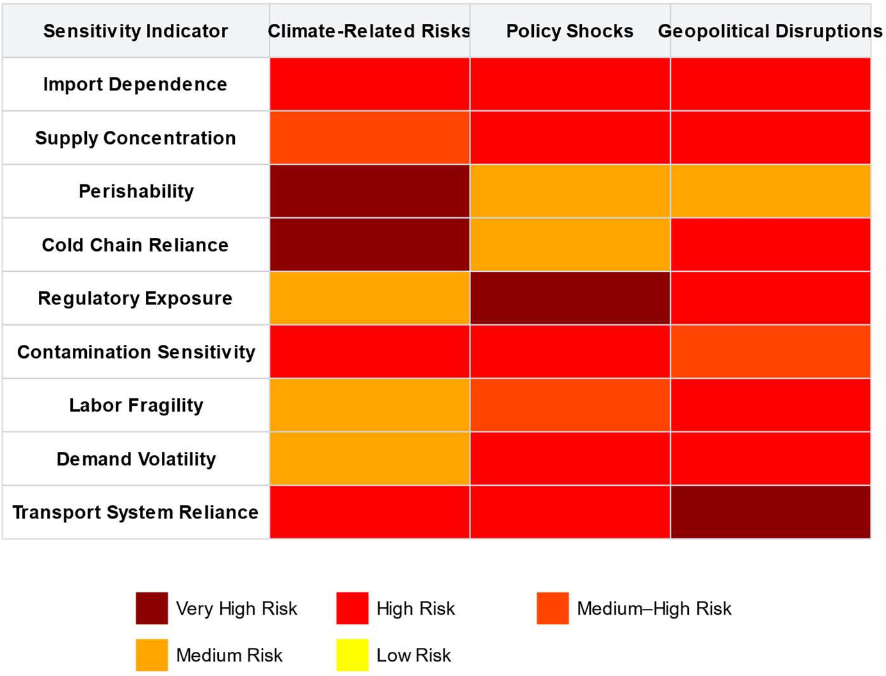

Figure 2. A visual representation of the risk typology matrix for fresh produce trade.

From the risk typology and based on the literature, we derive a rudimentary risk matrix (see Figure 3), connecting probability with impact at a global level. This risk matrix is highly general, as it must be adjusted for each country, region as well as each type of produce. However, it depicts a dire situation in which even siloed risks are significant, and the potential of them functioning in conjunction and, hence, leading to cascading effects is rather large, as evidenced in the previous thematic clusters.

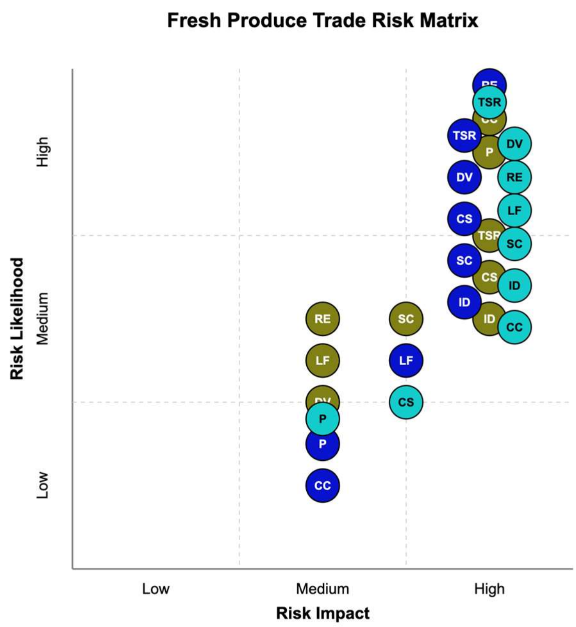

Figure 3. A rudimentary version of a literature-informed Risk matrix for fresh produce trade. **Legend for the Figure:** Climate-Related Risks – olive (color code: #808000), Policy Shocks – blue (color code: #0000CD, Geopolitical Disruptions – cyan (greenish blue, color code: #00CCCC). ID – Import dependence, SC – Supply concentration, P – Perishability, CC – Cold Chain Reliance, RE – Regulatory Exposure, CS – Contamination sensitivity, LF – Labor Fragility, DV – Demand Volatility and TSR – Transport system reliance.

This first methodological insight, exhibited in the typological risk mapping, tells us *what* and *how*, leading the way for the next two persectives: the *where* and the *how much*.

4. Results

Building on the findings from the previous section (a), we investigate towards proposing a multi-risk management approach that allows to (b) analyze flow-based sensitivities under compound, systemic shocks, and (c) simulate responses to multi-risk scenarios. The methods we use for this purpose are

- a visualization of the structural typology for global fresh produce trade by using Gephi and 2024 bilateral trade data from UN Comtrade, using HS-4 level product codes corresponding to fresh fruit and vegetable categories. Its results are presented in Section 4.1.
- a gravity model, stress tested with a compounded risk made of a climate event + a trade policy shock. Its results are presented in Section 4.2.

The two methods inform a discussion on the impact on sustainability and the interconnection between this topic and the systemic risks (see Section 4.3.) across three dimensions: (i) environmental (e.g., increased emissions and food waste); (ii) economic (e.g., price volatility, supply instability); and (iii) social (e.g., reduced access to affordable, nutritious food).

4.1. The Structural Typology of the Global Fresh Produce Trade

To properly use the Gephi visualization software, the data related to fresh produce trade had to be collected for 2024 for UN Comtrade at HS-4 level product codes corresponding to fresh fruit and vegetable categories, as follows:

- Vegetables (fresh): the entire HS 0701 to 0709 range.
- Fruits (fresh): the entire HS 0803 to 0811 range (nuts were excluded).

For analytical tractability, we limit the dataset to the top 20 exporters and top 20 importers of fresh produce and all their counterparts (vegetables and fruits, HS4 level), as ranked by total FOB trade value in 2024. We remove duplicates from the list of 40 and add China and Mexico. Thus, we have the following countries included:

- For vegetables: 25 countries: Argentina, Australia, Belgium, Brazil, Canada, Czechia, Denmark, Germany, Ireland, Italy, Japan, Malaysia, Myanmar, Netherlands, Poland, Portugal, Spain, Sweden, Switzerland, Thailand, Türkiye, United Kingdom, USA, Uzbekistan plus the People's Republic of China and Mexico
- For fruits: 29 countries: Argentina, Australia, Azerbaijan, Belgium, Brazil, Canada, Czechia, Denmark, Germany, Greece, Israel, Italy, Japan, Malaysia, Netherlands, New Zealand, Norway, Poland, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Türkiye, United Kingdom, USA, Uzbekistan plus the People's Republic of China and Mexico

The Gephi visualizations are thus build based on data at HS-4 level for the following 32 countries: Argentina, Australia, Azerbaijan, Belgium, Brazil, Canada, China, Czechia, Denmark, Germany, Greece, Ireland, Israel, Italy, Japan, Malaysia, Mexico, Myanmar, Netherlands, New Zealand, Norway, Poland, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Türkiye, United Kingdom, USA, Uzbekistan.

The Gephi visualizations work with nodes and edges. The nodes are countries involved, and the edges are directed trade relationships, represented by the trade volume (FOB value for exports and CIF value for imports). The larger the node, the bigger the importance of that particular country in the analyzed trade. The thicker the edge, the larger the trade flow, allowing to trace the dominant bilateral relationships. The node color refers to the modularity class which allows to detect communities. Each color shows a cluster of countries that trade more intensely among themselves than with others.

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First, we analyze with Gephi the situation for the 32 countries for **vegetables**. The initial generation issues 229 nodes and 1751 edges. As the initial visualization has too much noise, first, we filter out the edges (bilateral trade) lower than 1 million USD, to allow for a focus on structurally significant relationships. This results in 163 nodes and 662 edges. We run a modularity report to identify communities using the Gephi-suggested algorithm [88], and we implement the Yifan Hu graph drawing method [89] to generate the graph from Figure 4.

As can be noticed from the Figure, key actors in the vegetable trade are the USA, Germany, Spain, the Netherlands, witch USA – Mexico and Spain – Germany representing large trade flows. The pink cluster may be Europe-centric (e.g., Spain, Portugal, Italy, Netherlands), the blue cluster is the North American trade block (e.g., USA, Canada, Mexico), and the other colors, like green and orange, represent other regional or structural clusters. Other insights derived from the visualization:

- USA is the most likely largest fresh vegetable importer and connected to multiple clusters;
- Spain and Netherlands may act as re-export hubs in Europe;
- Mexico, Türkiye, Poland show up as likely strong regional suppliers;
- Germany appears as a central node with high import intensity from Southern Europe.

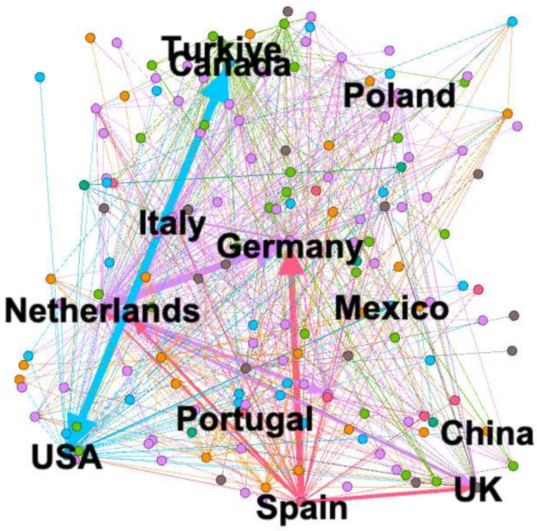

Figure 4. Global Trade Network of Fresh Vegetables (HS07) by FOB Value (2024).

We implement the same algorithm to generate the graph for fruits in Figure 5. It contains initially 230 nodes and 2324 edges. After filtering trade flows of larger than 1 million USD, the number of nodes is 171 and the number of edges is 929.

The graph shows that

- USA, Germany, Netherlands and Spain are highly key connected players ;
- Some countries (like Mexico and Canada) serve as bridge nodes between clusters, and they are structurally significant even if smaller in size;
- trade is not random rather but regionally or geopolitically clustered, as shown by the clear community structures (unlike the vegetable trade in Figure 4);
- More central nodes (like Germany or the Netherlands) have many high-volume connections and are likely hubs;
- Peripheral nodes are either low-volume traders or specialized exporters/importers with limited partners;
- The green cluster indicates strong intra-European or EU-centric fruit trade (with Germany, Netherlands, Spain);
- The purple cluster (which includes the USA) shows a different group of high-volume bilateral links (esp. with Mexico and Canada).

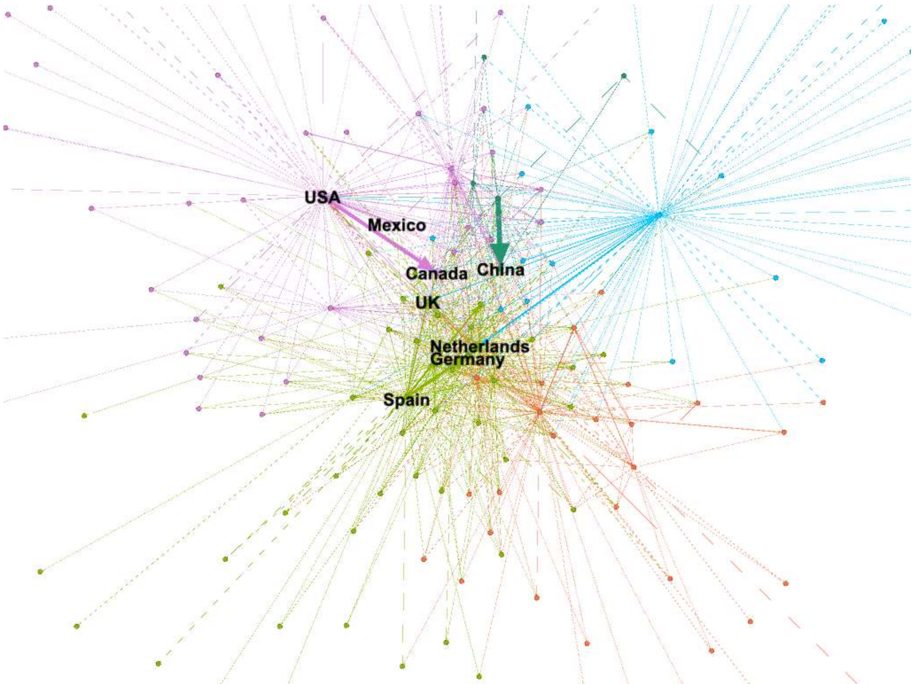

Figure 5. Global Trade Network of Fresh Fruits (HS08) by FOB Value (2024).

By analyzing the two images comparatively, it is easily noticeable that the fruits network is more radially structured and centralized (visible hub-and-spoke) around countries like the USA, Spain, and the Netherlands. In contrast, the vegetables network is denser and more interconnected, suggesting a more multipolar system. It has overlapping clusters and shorter path lengths which may be interpreted as it is more regionally connected via medium-sized hubs such as Germany, Poland or Türkiye. While the fruits network highlights sharper regional segmentation, the vegetables network indicates a more globalized, interwoven flow. The reasons for these significant differences may reside in perishability profiles, regional production specialization, or tariff/nontariff trade dynamics.

To present a clearer image of the situation for fresh produce (considering both vegetables and fruits), we run the algorithm again for the aggregate data, resulting in the map from Figure 6. After filtering to initial values of both vegetable and fruit trade of above 1 million USD, the network presented 170 nodes and 1003 edges.

The purple and orange communities represent areas with high-intraregional trade: Europe and South America. The green nodes are Southeast Asian and Oceania countries with niche roles, but less connectivity. The clear radial structures indicate dependency for smaller nodes which rely heavily on one or two hubs.

It is easily noticeable that there are several core hubs: Netherlands, Spain, Germany, Italy, made of exporting powers (Spain and the Netherlands), as well as importing and redistribution hubs (Germany, Italy). These hubs also act as cross-cluster bridges, linking different global communities. They are all part of the European Union.

Also noticeable is the North American cluster, in which the USA, Canada and Mexico form a distinct North American modular community, supported by the USMCA trade agreement. Moreover, the USA acts as both an importer and a significant intermediary to Latin America and Asia, seen in its extended network.

Albeit close to the core, China has moderate connectivity, while it interacts with multiple communities (Europe, North America, Asia). This status quo reflects its diverse sourcing and export relationships.

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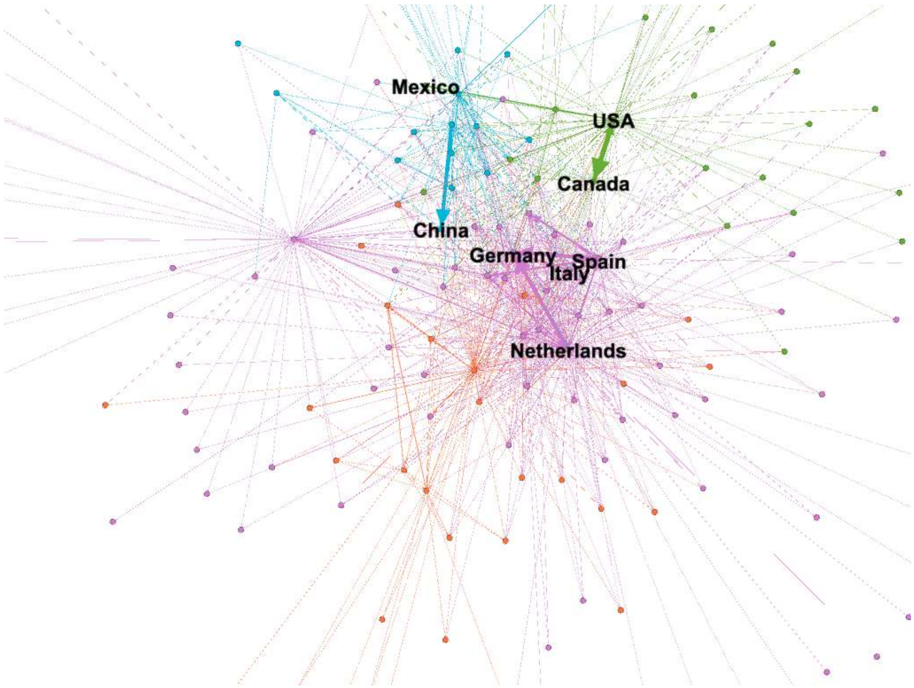

Figure 6. Global Trade Network of Fresh Produce (Fruits and Vegetables) (HS07 and HS08) by FOB Value (2024).

In terms of the vulnerability of the networks, and, in consequence, risks associated with them, the following takeaways are relevant:

- The **fruits** network:
  - is a highly centralized hub-and-spoke around Spain, the Netherlands and the USA. If any of these central nodes were disrupted (e.g., due to climate events, trade bans, or logistics breakdown), entire communities would be cut off, especially those with few alternative partners;
  - many nodes rely heavily on a single or few connections, indicating less resilience to shocks. More precisely, if a key edge is removed, rerouting may not be possible without major cost or time;
  - The communities are segmented, showing less inter-community spillover. This is both a positive (as it is good for containment of contamination and disease), and a negative (less flexibility), as a shock in one module may not be absorbed easily by others.
  - All these aspects make the fruit network rather fragile.
- The **vegetables** network:
  - has more overlapping connections, equating to multiple trade routes and redundancies. This makes the network more adaptable when individual countries or links are disrupted;
  - Trade appears more distributed across several medium hubs (Germany, Poland, Türkiye), not over-reliant on one node. That reduces systemic fragility. Moreover, most of these hubs are in the EU, so policy shocks are less probable.
  - There is more entaglement in the visualization, meaning there is greater interdependence, which may prove beneficial for rapid rerouting and resilience.
  - All these aspects make the vegetables network more robust (at least in comparison the fruit).
- The **aggregated fresh produce** network:
  - has moderate redundancy, therefore an increased resilience;
  - overall, central nodes (Netherlands, Spain, USA) are single points of failure. Their disruption could cascade across clusters.

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- Geographic clustering is evident: countries mostly trade within regional blocs but key global intermediaries link these blocs and act as both facilitators and bottlenecks / chokepoints;
- The existence of many peripheral nodes highlights limited integration of some producers or importers in global flows.
- The network is **globally integrated but asymmetrically dependent on key hubs, amongst which the USA**.
- Its resilience is uneven – some regions are very well-connected and more robust, with the potential for rerouting, while others rely on a few bridges.

The findings in this method serve as foundation, alongside the literature-informed typological risk mapping, for the simulation of compound risks on the gravity model in the following section. They underscore the crucial role the United States of America play in the fresh produce landscape, and, thus, the risk associated to this particular country in the entire network.

4.2. A Simulation of a Compound Risk Based on a Gravity Model

4.2.1. The Gravity Model

The first element prior to constructing the simulation is the development of the gravity model, according to the methodology.

The following data is to be collected:

- T_iUS: Value of fresh produce exports from country i to the United States. Data source: UN Comtrade (HS 07–08, USA imports only);
- GDP_i: Gross Domestic Product of exporter. Data source: World Bank WDI;
- Distance_iUS: Geographic distance between country i and USA. Data source: CEPII GeoDist (to U.S. only);
- Border_iUS: Dummy variable indicating shared border. Manual: 1 for Mexico, Canada; 0 otherwise;
- Tariff_iUS: Applied ad valorem tariff rate on fresh produce exports from country i to US. Data source: MacMap (to U.S. by HS6);
- SPS_iUS: Dummy variable for the presence of non-tariff SPS measures that constrain trade in perishables (1 = SPS restriction in place; 0 = otherwise). Data source: WTO SPS IMS database.

We collect UN Comtrade data for 2024 related to fresh produce trade, more precisely to US imports. The data is at HS-4 level product codes corresponding to fresh fruit and vegetable categories, as follows:

- Vegetables (fresh): the entire HS 0701 to 0709 range.
- Fruits (fresh): the entire HS 0803 to 0811 range (nuts were excluded).

This collection ensures comparability with the results of Section 4.1. Initial insights into the data show that:

- There are 50 countries from which the USA imports fresh produce
- Only 9 countries have more than 1% of the total imports. (see Table 6) and they are all in North and South America – proving the assertion about the regional focus of the US hub. They make up for 93.2% of the total imports in fresh produce by the US.

Table 6. Top sources for fresh produce imports in the USA, in 2024

Source country	Imports of Fresh Produce to US - %of total
Canada	8,74%
Chile	6,60%
Colombia	1,53%
Costa Rica	4,10%
Ecuador	2,33%
Guatemala	5,40%

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Honduras	1,48%
Mexico	53,83%
Peru	9,19%

The second term is GDP: data for 2024 was not available for all countries at the time of writing. As such, 2023 GDP values were used as proxies, assuming continuity in economic output (except for New Caledonia – with 2022 data, the latest available). For three sources of fresh produce imports there is no available data for GDP: Syria, Tonga, Other Asia (nes).

For the third term, distances, we use the Weighted distance, population-adjusted, with CEPII standard corrections, as it accounts for the distribution of population across the country and reflects the actual economic geography.

For the fifth term: tariffs: we rely on MAcMap-HS6 data for 2018 (source: WITS and [90]). We use the Effectively Applied Rates, which reflect the actual tariff in force during trade, including preferences under trade agreements. This is the most realistic input for the model simulating tariff shocks. The data is for USA as importer with the list of analyzed countries as exporters, for the year 2024. After data collection, a significant number of values are missing, therefore we use a simplified version: grouping countries as per US trade preference, and assigning tariff rate groups, extrapolated at country level, as follows:

- USMCA (Mexico, Canada) 0%;
- GSP or bilateral FTAs (e.g., Chile, Peru, Colombia) 0–1% (avg);
- WTO MFN (e.g., EU, China, India) 4.3%;
- Least Developed Countries (some Africa, etc.) 0% or GSP reduced;
- Others (fallback) 5%.

This approach both ensures methodological clarity, as the US Trade policy is (often) applied through structured trade regimes (e.g., USMCA, GSP, MFN) and it allows for WTO-compliant treatments. Moreover, as the gravity model simulates responses to relative price shifts, instead of pure regulatory texts, grouping tariff rates permits reducing the noise from marginal tariff differences without significant behavioral impact. Lastly, differentiating between 0%, reduced and MFN rates allows for accounting for trade cost tiers that influence flows most, as per literature cited in Section 3. Similar approaches are to be found in WTO impact assessments, GTAP-based models, and FAO trade resilience work and in research modeling general equilibrium shocks or climate-tariff compound risks [91–93].

This approach emphasizes systemic vulnerability, which is the main goal of this study, instead of granular tariff precision. From a sustainability perspective, this simplified mechanism refocuses the study on what matters most: exposure to structural trade costs, not the prediction of exact losses per country. This is in line with the extremely volatile trade environment as per April 2025 in the United States.

For the last term in the gravity model, the SPS dummy variable, by keeping in line with the focus on the overall vulnerability perspective, we create it heuristically (similar to follows recent practice in agri-trade modeling under data constraints as in [84] or [94]) based on whether the exporting country is known to face explicit SPS restrictions or complex import protocols for perishables into the U.S, as follows:

- Non-USMCA developing country: SPS_iUS-=1 if they export fresh fruits/vegetables and are frequently flagged in USDA/APHIS alerts or require complex phytosanitary certification.
- LDCs or countries with emerging markets: SPS_iUS-=1 if they are not covered by streamlined FTA phytosanitary frameworks.
- Others (EU, USMCA, Chile, etc.): SPS_iUS = 0 if they're under harmonized or aligned SPS standards.

The SPS dummy was cross-checked against public USDA/APHIS inspection alerts and WTO SPS notifications for selected countries. This cross-check confirmed that higher values generally aligned with stricter or more complex phytosanitary protocols.

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The gravity model is created by applying to this constructed database a regression in Excel, and its results are in Table 7.

Table 7. Gravity Model Regression Results for U.S. Fresh Produce Imports (2024)

Regression statistics	
Multiple R	0,58912645
R Square	0,34706997
Adjusted R Square	0,3147467
Standard Error	3,11425446
Observations	107

ANOVA	*df*	*SS*	*MS*	*F*	*Significance F*
Regression	5	520,690863	104,138173	10,737465	2,705E-08
Residual	101	979,556666	9,69858086		
Total	106	1500,24753			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	11,6157463	6,55463767	1,77214164	0,07938651	-1,3868916	24,6183843	-1,3868916	24,6183843
X Variable 1	0,85138992	0,18759345	4,53848419	1,5669E-05	0,47925497	1,22352487	0,47925497	1,22352487
X Variable 2	-1,965442	0,71220002	-2,759677	0,00687128	-3,3782553	-0,5526288	-3,3782553	-0,5526288
X Variable 3	1,29402861	2,68026655	0,48279848	0,63028366	-4,0228992	6,61095645	-4,0228992	6,61095645
X Variable 4	-0,3096853	0,16450321	-1,8825489	0,06263964	-0,6360155	0,01664478	-0,6360155	0,01664478
X Variable 5	-0,2443112	0,79903562	-0,3057575	0,76041857	-1,8293829	1,34076057	-1,8293829	1,34076057

R square = 0.347 and the significance F = 2.705E-08 indicate that the model as a whole is highly statistically significant, and it explains 34.7% of the variation in trade flows.

The rather limited influence may be affected by the application of the model for cross-country gravity models, especially with limited variables and heuristic inputs. Nonetheless, it may be considered a valid influence, as it is within the expected range for cross-country gravity models in agriculture, especially in case non-linear effects (e.g., SPS constraints) are included. As mentioned in [22], policy simulations often prioritize a balance between interpretability and fit over the maximization of predictive power. We adhere to this perspective, focusing on the vulnerabilities and shock simulations instead of the actual causal inference.

GDP and distance behave as expected with bigger and closer economies trading more; the SPS dummy is not statistically significant (probably also due to the heuristic construction and may represent a future work direction). The Border effect may be weaker because Canada and Mexico already trade at high levels, approaching saturation. Lastly, tariffs are close to significance and could be more impactful if modeled in more granularity (this again representing a future line of work). The interpretation for each coefficient is in Table 8.

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Table 8. Gravity Model Regression Results for U.S. Fresh Produce Imports (2024) - Interpretation

Variable	Coefficient	p-value	Interpretation
X1 (ln GDP)	+0.851	0.000015	Strong, positive effect — larger economies export more.
X2 (ln Distance)	-1.965	0.00687	Strong, negative effect — matches classic gravity theory.
X3 (Border dummy)	+1.294	0.630	Not significant — having a shared border did not help much in 2024.
X4 (Tariff)	-0.310	0.0624	Marginally significant — higher tariffs reduce trade (as expected).
X5 (SPS dummy)	-0.244	0.760	Not significant, but still directionally negative.
X1 (ln GDP)	+0.851	0.000015	Strong, positive effect — larger economies export more.

Model limitations and robustness considerations:

- The model uses trade values to predict trade outcomes. This may trigger an endogeneity risk and possibly lead to circular reasoning, as, for instance, countries with high trade flows might negotiate lower tariffs or harmonize SPS rules. However, the model is heuristic and aimed at a scenario-based sensitivity analysis instead of causal inference. This means that this particular limitation is unlikely to undermine the interpretive value of the results, as the potential for reverse causality does not impair the use of the model to simulate relative impacts under different policy shocks. It is also in line with similar literature [92–94].
- The use of 2023 GDP data as proxy for 2024 may be another limitation. However, given the historical continuity, the validation with the previous two steps of this methodology and the limited year-on-year variation for most exporters, we can assume that this substitution is not expected to bias the estimates significantly.
- Multicollinearity: markets with high tariffs may also impose non-tariff barriers. Considering the analysis runs on a small sample size and uses some regressors with categorical nature, a formal Variance Inflation Factor (VIF) analysis was not conclusive. However, no instability was detected in the estimated coefficients. We consider this to be a structural limitation and include it in future work.
- Due to data constraints, residual patterns were not formally tested but are acknowledged as a potential source of bias.

That being considered, we define the gravity model as:

$$\ln(T\_iUS) = 11.62 + 0.851*\ln(GDP\_i) - 1.965*\ln(Distance\_iUS) + 1.294*Border\_iUS - 0.310*Tariff\_iUS + -0.244*SPS\_iUS + e\_iUS \quad (3)$$

Where:

- T_iUS: Value of fresh produce exports from country *i* to the United States;
- GDP_i: Gross Domestic Product of exporter;
- Distance_iUS: Geographic distance between country *i* and USA;
- Border_iUS: Dummy variable indicating shared border;
- Tariff_iUS: Applied ad valorem tariff rate on fresh produce exports from country *i* to US;
- SPS_iUS: Dummy variable for the presence of non-tariff SPS measures that constrain trade in perishables;
- e_iUS: Error term.

4.2.2. The Scenario

The scenario used to stress-test the network on a multi-risk management approach is based on a single exogenous policy shock which evaluates the ripple effects of a major policy intervention by a central actor, more specifically, a 10% across-the-board tariff imposed by the United States of

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America on all fresh produce imports, increased to 25% for shipments from Mexico and Canada. The scenario starts on the real baseline tariff imposed by President Donald Trump on April 2nd, 2025, and it encapsulates both a plausible geopolitical and a protectionist policy shock with global systemic ramifications, mainly due to the central role of the country in the global produce flows.

This trade shock (which builds on the work of [21] based on the measures from the first Trump administration) is treated both as a standalone disruption and in a compound scenario alongside climate-related production losses.

The simulation uses a modified gravity model, with trade volume responses estimated using elasticity values ([21]), treated as heuristic parameters, not calibration outputs.

The simulation for the 10% across-the-board tariff for the United States uses the following method:

- We assume baseline trade values – as predicted from the gravity model. For this, we estimate a basic log-linear gravity model following equation (3) and calculate baseline trade values, corresponding to the exponentiated results of the log-linear equation.
- We assume the elasticity of trade to tariff shocks as -0.95 [21].
  - Baseline elasticity values used range from -0.8 to -1.2, depending on the commodity and source country, with demand-side price sensitivity assumed to remain constant across scenarios.
  - The chosen value aligns with [21] and other empirical simulations assessing the impact of U.S. import demand shifts. This holds in particular for Latin American exporters.
  - The elasticity is applied as a heuristic parameter, imposed based on credible external research. Thus, it allows us to simulate policy scenarios under plausible behavioral responses.
- The model outputs a predicted reduction in trade volumes and identifies the most affected exporters.
- We presume no retaliatory measures from the exporters.
  - This may simplify the analysis and isolate the sensitivity to U.S. tariff shocks
  - However, it is in line with current (as of April 2025) exporter behaviour looking to reduce the probability of a global trade war.
  - In a theoretical context, through, this assumption may understate systemic feedback loops in a real-world geopolitical scenario, as is the case with China, for instance.
  - This represents also a direction for future research.
- We revise trade flows following this equation:

$$\hat{T}_{iUS}^{tariff} = T_{iUS}^{baseline} \times (1 + \Delta\tau_{iUS})^{\varepsilon}, \quad (2)$$

Where:

- $\hat{T}_{iUS}^{tariff}$ is the adjusted trade volume after the tariff shock;
- $T_{iUS}^{baseline}$ is the predicted trade flow from the gravity model (from equation (1));
- $\Delta\tau_{iUS}$ is the change in tariff rate (e.g., from 0% to 10% or 25%);
- ε is the price elasticity of trade (e.g., -0.95).

By processing this algorithm, we find that in the first case (of solely a tariff shock – as per the real geopolitical event of April 2nd, 2025, there is a substantial decline in total import volumes (see Figure 7).

On average, countries see a reduction in trade ranging between 9.5% and 21%, depending on their tariff exposure. Countries with the highest tariffs (Mexico and Canada), as expected, show the most substantial absolute declines in trade volume. Notably, Mexico, which accounts for 59% of U.S. imports in fresh produce experiences a sharp absolute contraction due to both its tariff increase and central position. This effect is an important supply-side shock, with substitution capacity, as the percentage of imports provenant from Mexico is close to two-thirds of the overall US market. Taking into consideration the perishability, trade concentration and, in subsidiary, the diplomatic

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complications in securing and alternative supplier, the impact on the US national market may be considered as severe to societal resilience.

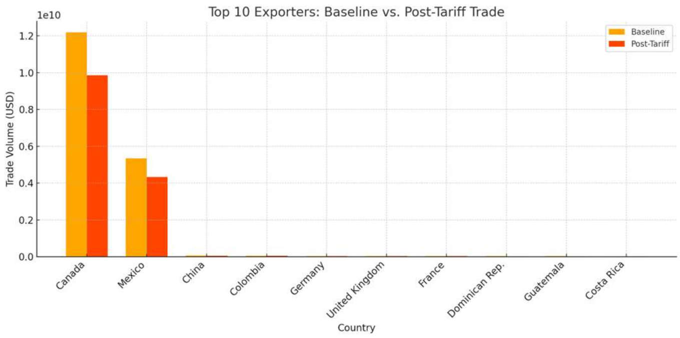

Figure 7. Baseline vs Post Tariff Trade volume for the top 10 exporters to US under the tariff shock scenario.

The blunt protectionist measure is considered in the second stage of our scenario in conjunction with a climate-change induced drought in Mexico. This risk is informed by [95] and resides in this context: "*Mexico's 2025 dry season could last around six months, according to predictions by the National Water Commission (Conagua) — from late November 2024 to May 2025 — meaning a potentially difficult year ahead in states by no means fully recuperated from drought conditions in 2024. 'The water crisis in Mexico is severe and represents a paradox because although torrential rains have occurred in recent months, drought persists in large areas of the country'". [95].*

We assume that this localized climate-change shock induces a 20% export loss for Mexico. This is another heuristic approximation and it is reductionist, as it assumes that all other countries are not affected. However, in reality, there are shifts in export capacity due to climate change which are not easily mitigated by technology. Thus, the two scenarios forming the compound multi-risk one are: Scenario 1: New tariff = 10% (all), 25% (Mexico, Canada) and Scenario 2: Same tariff + Mexico export reduction of 20% (climate shock). The algorithm indicates that the reduction in trade is even more significant for Mexico under the constraints of limited number of alternative routes or substituents (See Figure 8).

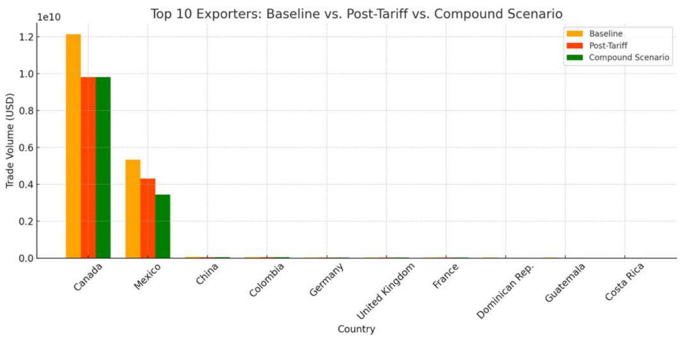

Figure 8. Baseline vs Post Tariff vs Compound Scenario Trade volume for the top 10 exporters to US under the multi-risk scenario.

With the resulting data from this scenario, we return to Gephi to respond to a series of questions: Does Mexico's centrality drop? Does another node rise (e.g. Costa Rica or Chile may gain influence as alternative routes?) Are communities more fragmented? Does US lose hub power? The new Gephi map, post-compound scenario is in Figure 9.

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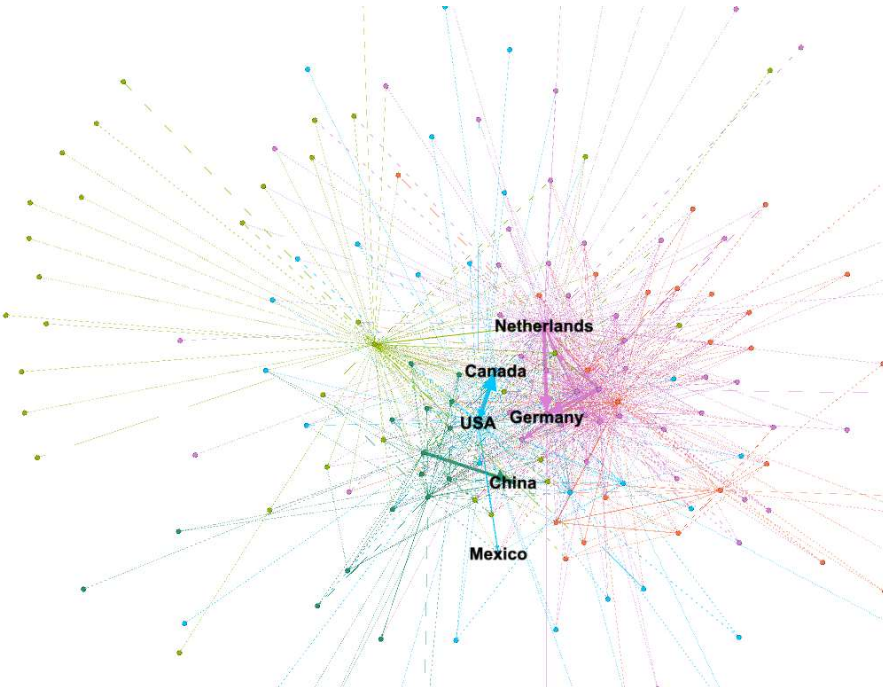

Figure 9. Global Trade Network of Fresh Produce (Fruits and Vegetables) (HS07 and HS08) by FOB Value (2024) under the multi-risk scenario.

The following insights may be observed: Mexico's weighted degree centrality drops significantly as it exports much less fresh produce to the U.S. There's no single replacement for Mexico as supplier for the US market, but a redistribution of trade flows strengthens secondary hubs, such as Chile, Costa Rica, Colombia and Peru. However, this considers that the US market retains its purchase power and no other risks are compounded to reduce it. Mexico has a hub role linking Latin America to North America, and its weakening reduces intermodular connectivity, leading to slightly more fragmented or regionalized clusters. The U.S. retains centrality due to its global trade volume but suffers a decline in connectivity strength with key partners, especially in Latin America. This assumption is, of course, under this reductionist compound scenario, in which no other elements affect the situation.

5. Sustainability Implications and Other Conclusions

The study offers a multi-risk management integrative method to analyze the structural vulnerabilities and flow-based sensitivities in the global produce trade system. It works towards demonstrating that the current configuration of fruit and vegetable trade flows are highly sensitive to exogenous shocks, as they are structurally centralized and increasingly fragile. The research uses the United States of America as a simulation case, due to its position as a global hub, but also due to its current trade policy volatility, as the main focus of the study is to focus on governance issues, rather than technical fixes (such as SPS harmonization or the food reserve systems). The vulnerability induced in the system by the fact that a global trade hub like the USA imports over 90% of its fresh produce from a tightly clustered group of Latin American countries (at climate change risk) and, moreover, behaves eratically in terms of trade policy. The structural dependency is exacerbated by perishability, cold chain reliance, as proven by literature, just to make the interconnectedness of risks even greater, and is underscored by the simulation scenarios. Even unilateral protectionist moves when compounded with climate induced localized risk events depress trade flows and fragment the network's connectivity.

This fragility has both sustainability, resilience and governance implications:

- It is almost a truism that sustainability in food systems depends on both environmental and logistical resilience and diversifying sourcing strategies should become part of a sustainability

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agenda. This is underlined by the risks raised by, for instance, the current concentration of U.S. import dependence on a narrow set of regional suppliers.
- The poli-crisis and multi-risk VUCA world (volatile, uncertain, complex and ambigous) reveal a high risk for critical supply chains destabilization, as caused by converging events in a "perfect storm" scenario. In this context, it is crucial to develop integrative governance frameworks that address multiple risks in conjunction.
- In all disruption scenarios, the small exporters are at risk. This raises questions about local and global societal resilience and how mitigation mechanisms may be at play.
- Another truism comes from the need for redundancy as multi-risk mitigator. Particularly in terms of fresh produce, this translates into multiple, overlapping supply routes, with proper cold chain infrastructure.

Risk-informed governance, including anticipatory policy tools, as well as data-driven decision-making, represent other significant risk mitigators, and this study comes to fill such a landscape. It offers a tool for anticipatory governance and allows policymakers to assess system-wide tradeoffs before shocks occur. It provides evidence that fresh produce trade is facing a convergence of risks that cannot be adequately addressed through siloed approaches. This particular range of products in global trade are essential for human well-being and thus, their adequate provision, in all countries, is more than fundamental for societal resilience.

Albeit ambitious, the study suffers from a heuristic approach and several reductionist decisions, in a setting of policy rather than causal inference. Future research should address these challenges and, for instance, refine the compound scenario modeling by incorporating dynamic elasticity values, differentiated by product type and seasonality. Another potential direction is to integrate climate foresight models with network-based trade analytics and / or to couple with other risk factors from sources such as trade finance, logistics chokepoints, or geopolitical risk indices.

Fresh produce is where the multi-risk context becomes tangible, both for countries and for people, so that is why this is the perfect spot to start properly addressing societal resilience, through whichever means necessary.

Author Contributions: Conceptualization, methodology, validation, formal analysis, resources, data curation, writing, R.V-D. The author read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	**Full Term**
AfCFTA	African Continental Free Trade Area
CAGR	Compound Annual Growth Rate
CEPII	Centre d'Études Prospectives et d'Informations Internationales
FAO	Food and Agriculture Organization
FOB	Free on Board
GSP	Generalized System of Preferences
HS	Harmonized System (tariff classification)
LDC	Least Developed Country
MFN	Most Favored Nation
NAFTA	North American Free Trade Agreement
SPS	Sanitary and Phytosanitary Measures
SDG	Sustainable Development Goal
UN Comtrade	United Nations Commodity Trade Statistics Database
USMCA	United States–Mexico–Canada Agreement
VUCA	Volatile, Uncertain, Complex, and Ambiguous
WTO	World Trade Organization

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Appendix A

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