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LETTER

# Optimization of national grain imports to balance risk and return: a portfolio theory approach

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## Abstract

Global grain trade plays a key role in food security. Many nations rely on imported grain to meet their dietary requirements. Grain imports may be at risk due to weather shocks, economic crises, or international conflicts. Countries aim to balance import risk with the expected return of their grain supplies. This research brings these dual objectives together in an innovative modern portfolio theory framework. Modern portfolio theory provides a set of concepts to formulate the trade-off between risk and expected return in national grain imports. Using Markowitz's mean-variance optimization model, we identify opportunities to reduce risk in existing national grain import accounts, without increasing costs under realistic supply mass constraints of trade partners. Several major grain importers may be able to reduce risk in their grain imports without increasing cost, such as wheat imports in Egypt, maize imports in Vietnam, and rice imports in Saudi Arabia. However, some countries would indeed have to pay more to achieve more stable grain supplies, such as wheat imports in Turkey. This study provides a framework to quantify the different costs, benefits, and levels of risk in grain trade that can inform future research and decision-making.

## 1. Introduction

Grain trade promotes global food security (Sartori and Schiavo 2015, Seekell *et al* 2018), especially so in certain importing nations (Hellegers 2022). Yet, grain imports often require balancing the cost of grain supplies with their expected volatility. For example, a country could choose to purchase grain from the cheapest providers, but those supplies may be more susceptible to shocks. Recent trade disruptions have highlighted the importance of considering supplier risks and diversification (Gomez *et al* 2021, Doğan *et al* 2023). During the global COVID-19 pandemic, Cambodia and Myanmar, among others, imposed a complete export ban on rice (Koppenberg *et al* 2021), raising domestic prices elsewhere and negatively impacting Africa's rice consumption stocks (Kathiresan *et al* 2020). In 2022, wheat exports from Ukraine were halted due to Russia's invasion, threatening the food security of many Middle East and North Africa nations, such as Egypt, Turkey, and Lebanon (Behnassi and El Haiba 2022). Modern portfolio theory (Markowitz 1952) is a quantitative framework that can be used to identify the costs, benefits, and levels of risk of different grain import portfolios. The mean-variance optimization model can help decision-makers evaluate how to provide stable grain supplies while also considering cost.

Trade expands access to affordable grain supplies (Trela *et al* 1987, Donaldson 2018). The need to enhance resilience to risks in global grain trade has received increased attention in the literature recently (Puma *et al* 2015, Seekell *et al* 2017, Gomez *et al* 2021). However, these important dual objectives of grain trade—ensuring both affordable and stable supplies—have not yet been brought together in a modern portfolio theory framework. Modern portfolio theory was developed in financial economics for investment managers to choose from a pool of assets with varying rates of return (Markowitz 1952). Modern portfolio theory helps investors reduce their risk by holding a variety of assets whose returns are not perfectly correlated. In addition, the mean-variance optimization model systematically chooses the combinations of assets that would yield the maximum returns at the lowest possible risk (Markowitz 1952). Portfolio theory has been applied beyond the financial context to water resources planning (Beuhler 2006, Paydar and Qureshi 2012, Herman *et al* 2014), ecosystem services (Alvarez *et al* 2017, Ando *et al* 2018), biodiversity conservation (Ando and Mallory 2012, Hoekstra 2012), energy supplies (Stringer 2008, deLlano-Paz *et al* 2017), and agri-food production (Castro *et al* 2015, Knoke *et al* 2015, Khanal and Mishra 2017), among others. The portfolio theory is comparably suitable to capture the risk-return trade-offs that exist in national grain imports.

Grain trade requires the consideration of grain supply constraints since countries are restricted to exporting quantities of grain within their trade limits. This supply constraint makes the application of mean-variance optimization to grain trade different from the original mean-variance optimization in the context of stocks and other liquid assets, which do not necessitate mass balance considerations. As such, we develop a mean-variance optimization model with supply mass constraint to propose both *optimal* and *optimum* grain import portfolios for each nation individually. Optimal grain import portfolios ensure minimum price volatility under a cost constraint, whereas optimum grain import portfolios ensure minimum price volatility without any cost constraint. In this study, we identify both optimal and optimum portfolios to determine opportunities for importer nations to achieve more stable and diverse grain supplies, while also acknowledging economic considerations.

This paper contributes to the growing literature on the trade-offs in global supply chains and trade. The research questions that guide this study are: (1) What is the relationship between risk and return in grain import portfolios? (2) What is the relationship between diversity and risk in grain import portfolios? (3) What are the national optimal and optimum grain import portfolios? Answering these questions will determine the viability of applying modern portfolio theory to national grain trade. The findings quantify the different costs, benefits, and levels of risk in grain trade, which may be informative for future agri-food trade research and policy.

### 1.1. Portfolios for grain import

The portfolio approach was developed for application in finance to assess the risk and return of asset investing (Markowitz 1952). It is a flexible decision-making tool that seeks to either maximize the expected return or minimize the collective risk among alternative portfolios of assets (Elton and Gruber 1997). Portfolio theory encourages individual decision-makers to diversify their investments, such that 'all eggs are not put in a single basket' (Fraser *et al* 2005). Here, we use modern portfolio theory to assess the risk vs expected return for grain trade. Specifically, we focus on grain imports since these grain supplies are a key part of domestic food security (Donaldson 1984).

In this study, each importer nation represents a portfolio manager and every exporter nation is an available asset that could be invested in. Here, the fraction of investment in each asset is represented by import mass share. The return of each asset is defined to be the weighted average unit value of import ($\$\,\mathrm{kg}^{-1}$). The unit value of import is also the cost paid by the portfolio manager. For grain imports, a major goal of the portfolio manager is thus to minimize return (i.e. cost). This makes the application of modern portfolio theory to grain trade distinct from asset investing, which aims to maximize return (i.e. profit). We consider both cross-sectional and panel risk. The portfolio cross-sectional risk is defined to be the variance in unit value ($\$\,\mathrm{kg}^{-1}$) across the invested assets (i.e. exporters) in a single time period (Bollino and Galkin 2021). The portfolio panel risk is the collective covariance in unit value ($\$\,\mathrm{kg}^{-1}$) across the invested assets (i.e. exporters) through time (Markowitz 1956). Thus, cross-sectional risk is used in the trade-off analysis between risk and return, whereas panel risk is used in the mean-variance optimization model.

A mean-variance optimization model was developed to identify less risky grain import portfolios with and without cost considerations. To optimize a portfolio, the manager aims to minimize the collective volatility across trade partners (i.e. assets) through time. The minimum covariance helps asset managers (i.e. importers) invest in assets whose change in unit value ($\$\,\mathrm{kg}^{-1}$) is not positively correlated through time. The portfolio manager optimizes by investing in assets that both increase and decrease in cost at the same time to stabilize its return. This approach means that grain importers minimize the cost covariance across their assets (i.e. trade partners) to reduce uncertainty in unit value. The optimization of national grain import portfolios allocates trade to exporters with available mass while minimizing the volatility in import cost. A supply mass constraint is used to ensure that exporters have the ability to meet the optimized portfolio of each importer nation one at a time.

## 2. Methods

### 2.1. Data sources

We use annual 'import' reports from COMTRADE (UNCOMTRADE 2020) both in value ($) and mass (kg) that are reported by the importer nations for the years 2008–2020. Trade data is organized as a square matrix with exporters in the rows and importers in the columns. Separate matrices are constructed for the wheat, maize, and rice trade in units of mass (kg) and value ($). Then, we divide the total import value ($) by the total import mass (kg) between every exporter and importer nation to obtain the 'unit value ($\$\,kg^{-1}$) of the commodity per trade relationship'. Our cost measure represents the Cost-Insurance-Freight of a commodity that is experienced by the importer nation which includes insurance and transportation (FAOSTAT 2020, Chen *et al* 2022). Hence, the import unit cost is generally higher than the corresponding export unit cost.

Data for the year 2020 serves as the most up-to-date empirical case to evaluate the trade-off between cross-sectional risk and return in grain import portfolios. Data between 2008–2019 is used to calculate the mean and covariance in unit value of import ($\$\,kg^{-1}$) through time for determining the optimal and optimum portfolios.

### 2.2. Key terms and equations from modern portfolio theory

Here, we explain how we apply the modern portfolio theory concepts of expected return, risk, and diversity to grain trade. For a single time period, the expected return of grain imports is defined to be the weighted average in the unit value ($\$\,kg^{-1}$) of each commodity. The cross-sectional risk of the grain import portfolio is given by the variance of its return (i.e. cost) among the assets (i.e. exporters) (Bollino and Galkin 2021). Expected return $E_j$ and cross-sectional risk $R_j$ of the importer $j$ are given in equations (1) and (2), respectively. The mass share of imports provided by each exporter $i$ is represented by $w_i$, and $c_i$ is the unit value of the commodity ($\$\,kg^{-1}$) charged by exporter $i$ to the importer $j$ (see SI for more detail).

$$E_j = \sum_{i=1}^{N} w_i \times c_i \tag{1}$$

$$R_j = \text{var}\,(w_i \times c_i)\;\; i = 1, \ldots, N \tag{2}$$

The Herfindahl–Hirschman Index (HHI) is used to calculate the portfolio diversity of each importer $j$ and is given in equation (3). Lower HHI values indicate the mass shares are more evenly distributed among a greater number of suppliers, hence more diverse import portfolios (Rhoades 1993).

$$HHI_j = \sum_{i=1}^{N} w_i^2 \tag{3}$$

We first assess the relationship between expected return $E_j$ and cross-sectional risk $R_j$ in the grain portfolios of each importer $j$ for a single year. We use 2020 empirical trade data to compute $E_j$ and $R_j$. Modern portfolio theory encourages a diverse set of investments to reduce risk. In our case, this corresponds to importing from a diverse set of grain suppliers. Thus, we also assess the relationship between diversity $HHI_j$ and cross-sectional risk $R_j$ in grain portfolios of importer nations for the year 2020. These analyses lay the foundation for the mean-variance optimization model approach, and the observed risk vs. return trends in grain imports motivate the proposal of optimal and optimum portfolios.

### 2.3. Markowitz mean-variance optimization model

To identify optimal and optimum portfolios, we develop a mean-variance optimization model with an exporter mass supply constraint as in equations (4)–(8). The mean-variance optimization is a data-driven model which requires historic trends in the unit cost to compute its mean and covariance (Markowitz 1956). So, trade data from 2008–2019 that is specific to each grain commodity and importer nation is used to compute the expected return and panel risk of potential portfolios. The optimization model is formulated to be run individually for each major grain importer $j$ to propose alternative portfolios for the year 2020 based on historical data (see SI for more detailed information on the optimization model).

The decision that is being made by the model for each importer nation is: 'How much to import from which available exporters for the year 2020, to minimize the portfolio risk?' By design, generally, more

**Table 1.** Key terms and their definitions in this study.

| Term | Definition |
|---|---|
| Return | Weighted average in the unit value ($\$\,\text{kg}^{-1}$) of imported grain crops. |
| Cross-sectional risk | Volatility in unit cost among exporters in a single year. |
| Panel risk | Volatility in unit cost among exporters through time. |
| Reliability | Logistical, environmental, and governmental performance of suppliers (see SI). |
| Diversity | Distribution of mass shares across suppliers. |
| Optimal portfolio | Import portfolio that minimizes panel risk while keeping the unit cost constant. |
| Optimum portfolio | Import portfolio that minimizes panel risk without any cost constraints. |

diverse portfolios are proposed by mean-variance optimization model i.e. more even mass share distribution across multiple exporters to reduce the panel risk.

$$\min_{w} [w]^{T} \times [cov] \times [w] \tag{4}$$

$$\text{s.t.} \sum_{i=1}^{N} w_i = 1 \tag{5}$$

$$\sum_{i=1}^{N} w_i \times c_i = E_j \tag{6}$$

$$D_j \times w_i \leq S_i \; \forall i \in N \tag{7}$$

$$1 \geqslant w_i \geqslant 0 \; \forall i \in N \tag{8}$$

For each importer nation $j$, we run the mean-variance optimization model individually and propose two separate portfolios: optimal and optimum (i.e. proposals for 2020). For the optimal portfolio (i.e. with cost constraint), we run the presented version of the model. For the optimum portfolio (i.e. without any cost constraint), we run the presented model without the second constraint (equation (6)). Thus, optimal and empirical portfolios in 2020 per importer nation $j$ have the exact same unit cost, $E_j$. However, optimum portfolios are not bounded by any specific cost.

The mass supply constraint (equation (7)) ensures that each exporter has the capacity to meet the portfolio requirements of the importer $j$, which we assume to be a small open economy. Policies in small open economies do not alter world prices, i.e. these nations take world prices as given, which is a common assumption in macroeconomics (Vegh 2013). Even though case study nations are small open economies, their total demand could be high enough that multiple exporters might be required to allocate supply. Thus, to enhance the realism of our approach, each exporter's capacity is bounded by its available export supply mass.

A summary of the key terms in our study and their definitions are listed in table 1.

## 3. Results

In this section, we present the results for each research question in detail. First, we quantify the relationship between risk and return, as well as risk and diversity in grain import portfolios. Results we present in sections 3.1 and 3.2 are based on the realizations in 2020, as they are directly calculated with empirical data. We find that there is indeed a positive relationship between risk and return. However, the implication of this positive relationship is different than its counterpart in the financial stock market, since it means that higher costs accompany greater risk in grain imports, whereas asset managers seek higher returns with higher-risk investments.

Motivated by this positive relationship between return (cost) and risk in grain imports, we proceed to apply the mean-variance optimization model to examine whether we can propose portfolios that better balance risk and return. We compare the empirical portfolios in 2020 with the optimal and optimum portfolios (i.e. proposals) that are obtained through the optimization model for case study grain importing nations. The proposed optimal and optimum import portfolios serve as benchmarks for these nations to consider since they represent less risky and less costly supplier selections than their empirical situations in 2020.

Case study nations are selected that are among the top 10 mass importers of a grain commodity as seen in table 2. Additionally, the case study nations are small, open-economies that take world prices, rather than set them, such that their import decisions would not significantly affect global prices. These countries also have

**Table 2.** Top 10 mass importers of wheat, maize, and rice in 2020 by UNCOMTRADE data.

| Rank | Wheat Importer | Total Mass (kg) | Rank | Maize Importer | Total Mass (kg) | Rank | Rice Importer | Total Mass (kg) |
|---|---|---|---|---|---|---|---|---|
| 1 | Indonesia | $1.03 \times 10^{+10}$ | 1 | Japan | $1.58 \times 10^{+10}$ | 1 | China | $1.95 \times 10^{+9}$ |
| 2 | Egypt | $9.58 \times 10^{+9}$ | 2 | Vietnam | $1.21 \times 10^{+10}$ | 2 | Saudi Arabia | $1.51 \times 10^{+9}$ |
| 3 | Turkey | $9.46 \times 10^{+9}$ | 3 | Republic of Korea | $1.17 \times 10^{+10}$ | 3 | Ethiopia | $1.33 \times 10^{+9}$ |
| 4 | China | $8.15 \times 10^{+9}$ | 4 | China | $1.12 \times 10^{+10}$ | 4 | USA | $1.17 \times 10^{+9}$ |
| 5 | Italy | $7.99 \times 10^{+9}$ | 5 | Egypt | $8.51 \times 10^{+9}$ | 5 | Senegal | $1.04 \times 10^{+9}$ |
| 6 | Philippines | $6.18 \times 10^{+9}$ | 6 | Spain | $8.14 \times 10^{+9}$ | 6 | South Africa | $1.02 \times 10^{+9}$ |
| 7 | Brazil | $6.16 \times 10^{+9}$ | 7 | Colombia | $6.16 \times 10^{+9}$ | 7 | Brazil | $9.68 \times 10^{+8}$ |
| 8 | Morocco | $5.52 \times 10^{+9}$ | 8 | Italy | $5.99 \times 10^{+9}$ | 8 | Benin | $8.71 \times 10^{+8}$ |
| 9 | Japan | $5.37 \times 10^{+9}$ | 9 | Netherlands | $5.94 \times 10^{+9}$ | 9 | United Kingdom | $7.63 \times 10^{+8}$ |
| 10 | Netherlands | $4.31 \times 10^{+9}$ | 10 | Malaysia | $3.85 \times 10^{+9}$ | 10 | Niger | $7.15 \times 10^{+8}$ |

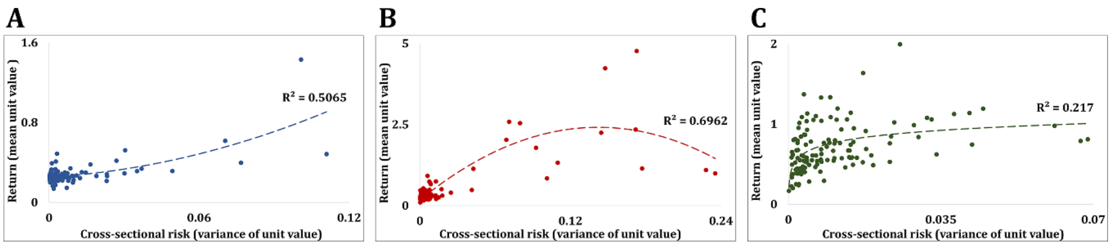


**Figure 1.** Relationship between cross-sectional risk ($R_j$) and return ($E_j$) for grain import portfolios by crop without the outliers (see SI). Each point represents the empirical import portfolio of a nation for (A) wheat, (B) maize, and (C) rice in 2020. Points closer to the origin have lower returns (i.e. costs) and less risky imports.

a significant population facing food insecurity. Therefore, balancing risk-return-diversity in their staple grain imports is crucial for the affordability of their grain supplies, with implications for the well-being of their citizenry, and the stability of their economy and government. Note that we provide optimized portfolios for additional countries within the top 10 importers for each crop in the SI.

### 3.1. What is the relationship between risk and return in grain import portfolios?

The relationship between cross-sectional risk $R_j$ and return $E_j$ in grain import portfolios is shown in figure 1. There is a positive relationship between cross-sectional risk and return in 2020 for wheat, maize, and rice import portfolios, respectively. This positive relationship means that high-risk import portfolios also have a higher return, as in the application of portfolio theory to financial instruments. However, this also means that nations with more risk in their grain imports also pay more for those imports. This is because, unlike the application of portfolio theory to finance, here the return captures the cost paid by the importer. Thus, importing nations aim to minimize both risk and return/cost. However, our observation indicates that importer nations are not paying higher costs to achieve greater resilience. In fact, even though they are paying higher costs, they are subject to higher import volatility.

### 3.2. What is the relationship between diversity and risk in grain import portfolios?

Asset diversification is not the main objective of portfolio theory but is an important component as it relates to portfolio risk and reliability (see SI for more detailed information on portfolio reliability). The relationship between diversity $HHI_j$ and cross-sectional risk $R_j$ in grain imports is shown in figure 2. We observe that there exists a positive relationship between diversity ($HHI_j$) and cross-sectional risk ($R_j$). Note that higher values of HHI indicate lower levels of diversity, so the positive relationship indicates that risk increases as diversity decreases. This means that more diverse portfolios also provide lower volatility in the cost of import. If there was a shock in a supplier and its grain supply was lost, the importers with more diverse portfolios (lower $y$-axis values) would experience less change in their average unit cost of import (lower $x$-axis values). Thus, more diverse portfolios are also less risky as found in modern portfolio theory. This finding corroborates recent work that shows that increasing diversity in food supplies reduces supply chain vulnerability to risks (Gomez *et al* 2021).

We also perform additional portfolio diversity analysis that considers the reliability of different exporters in terms of their governmental (WGI, 2020b), environmental (EPI, 2020), and logistical (LPI, 2020a) performance. The assessment of the exporters' reliability stems from the fact that nations do not have uniform supply chain attributes. Based on supplier selections and trade dependencies, importer nations could be subject to more disruptions across their international trading network. For example, some

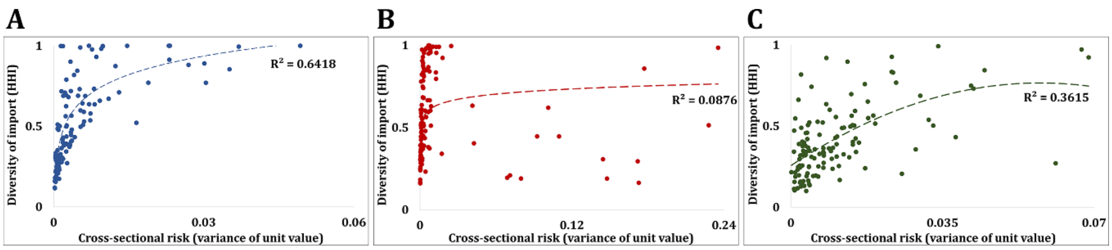


**Figure 2.** Relationship between diversity ($HHI_j$) and cross-sectional risk ($R_j$) for grain import portfolios by crop without the outliers (see SI). Each point represents the import portfolio of a nation for (A) wheat, (B) maize, and (C) rice in 2020. Points closer to the origin have more diverse (i.e. lower HHI) and less risky portfolios.

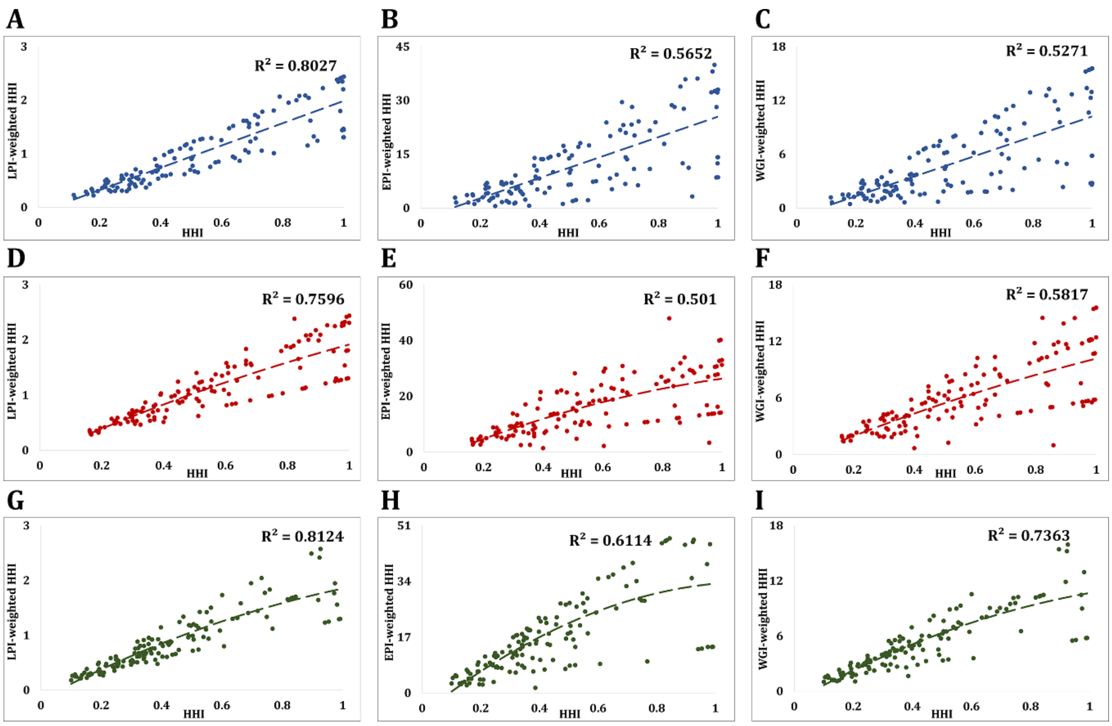


**Figure 3.** The relationship between diversity ($HHI_j$) and reliability indices-weighted diversity of each nation's grain import portfolio in 2020. (A)–(C) Wheat imports, (D)–(F) Maize imports, and (G)–(I) Rice imports. (A)–(D)–(G) represent logistical performance indices (LPI), (B)–(E)–(H) represent environmental performance indices (EPI), and (C)–(F)–(I) represent governmental performance indices (WGI) of suppliers. Importer nations that are closer to the origin have higher diversity (i.e. lower HHI), and are inherently more reliable suppliers in their grain imports.

exporters tend to experience more internal conflicts, less adaptability against climate change, and not well-automated supply chains. Importer nations that rely on these less reliable suppliers are likely to be subject to more disruptions in their import supplies (see SI for a more detailed explanation of the reliability indices and their calculation).

In figure 3, the observed positive relationship between diversity and reliability indices-weighted diversity (Goddin 2019) of import portfolios is illustrated (see SI for a more detailed explanation of the reliability indices-weighted diversity). This positive relationship indicates that importers with less diverse portfolios (higher HHI values) also have less reliable suppliers (higher reliability indices-weighted HHI values), whereas more diverse import portfolios are composed of more reliable exporters. This is consistent across the governmental, environmental, and logistical performances of exporters. Thus, increasing diversity in supplier selections also improves the logistical, environmental, and governmental reliability of import portfolios. This relationship supplements previous literature and our findings on the benefits of import portfolio diversity against supply chain shocks (Gomez *et al* 2021).

### 3.3. What are the national optimal and optimum grain import portfolios?

The observed positive trade-off between risk and return highlights the fact that importer nations do not achieve less risky portfolios by paying more for their grain imports. On the contrary, nations that pay more

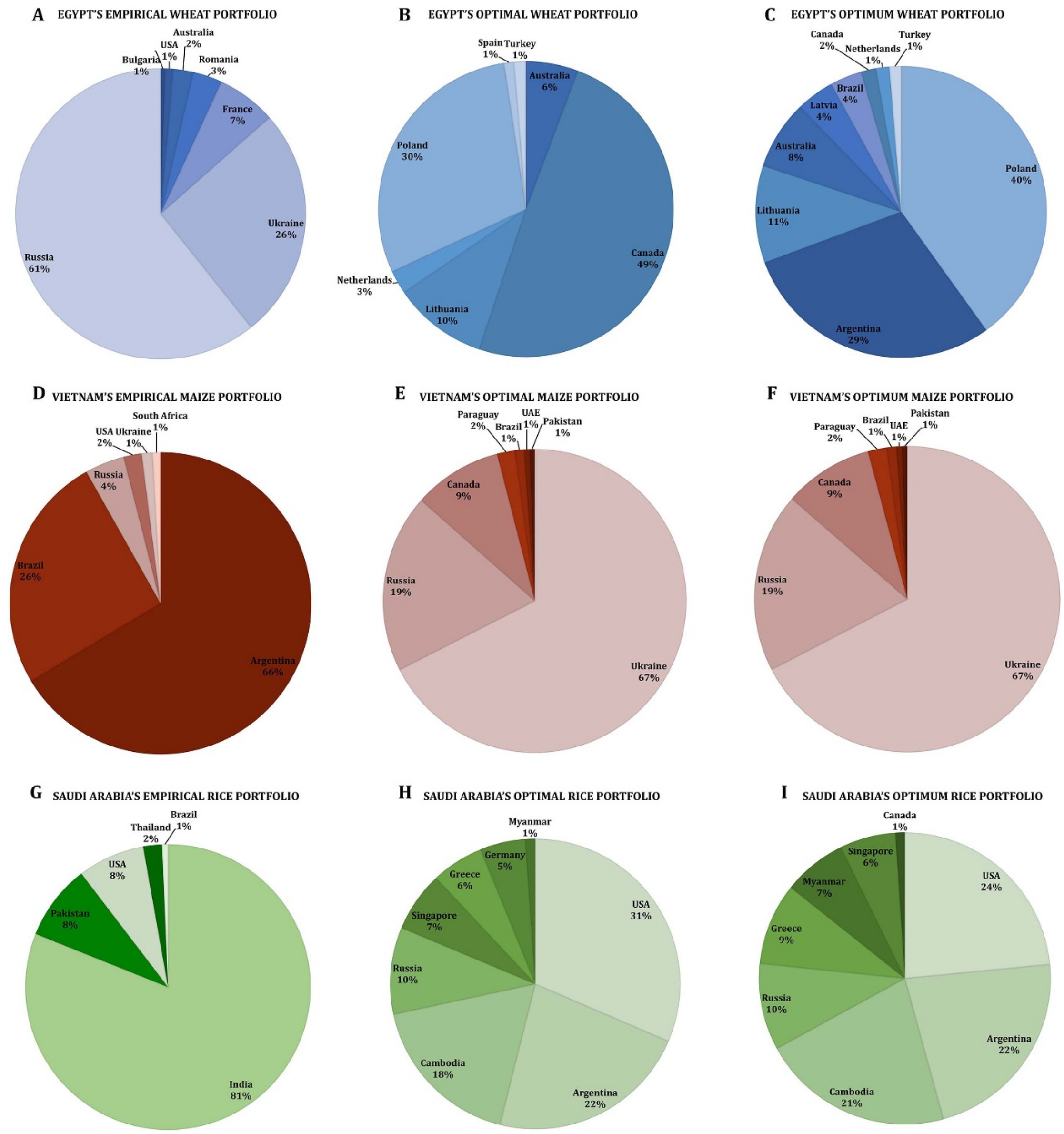


**Figure 4.** Empirical, optimal, and optimum grain import portfolios for case study nations in 2020. Supplier mass shares for (A)–(C) wheat imports of Egypt, (D)–(F) maize imports of Vietnam, and (G)–(I) rice imports of Saudi Arabia. (A)–(D)–(G) Empirical portfolios (i.e. realizations), (B)–(E)–(H) Optimal portfolios (i.e. proposals with cost constraint), and (C)–(F)–(I) Optimum portfolios (i.e. proposals without cost constraint).

are subject to higher volatility in their imports in case of a disruption in one of their suppliers. This empirical conclusion leads us to consider whether importers could achieve less risky portfolios through adjustments in their supplier selections and proportions. Is it possible to uncover grain import portfolios with lower volatility and a more diverse set of suppliers, that are also economically attractive?

To answer this question, we develop a mean-variance optimization model and propose optimum and optimal portfolios for major grain importers individually. The case study nations are Egypt for wheat import, Vietnam for maize import, and Saudi Arabia for rice import. Note that these low-income and generally food-insecure nations are selected from the list of the top 10 importers of each grain commodity (see table 2). Through optimal and optimum portfolios, the model allocates how much to import from available exporters to minimize the panel risk for each nation in 2020.

Figure 4 compares the mass share distribution to the available suppliers for the empirical, optimal, and optimum portfolios. Empirical portfolios indicate the real-world import scenarios for the case study nations in 2020 (figures 4(A)–(D)–(G)). Optimal portfolios show minimum panel risk while keeping the import cost constant (figures 4(B)–(E)–(H)). Optimum portfolios for these nations minimize panel risk without cost constraint (figures 4(C)–(F)–(I)). This approach enables us to identify grain import portfolios that are less

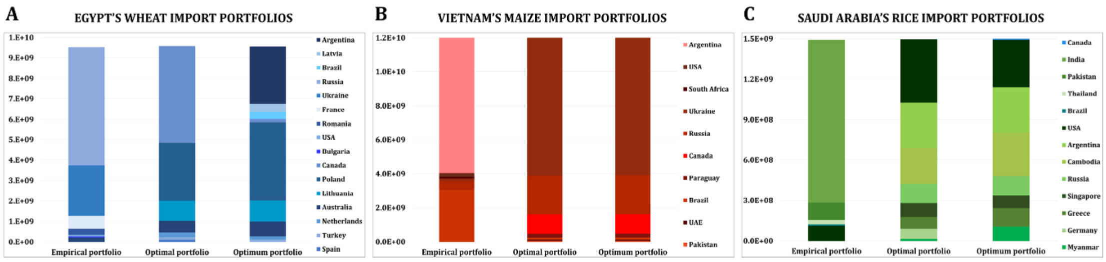


**Figure 5.** Composition of mass imports for case study nations. The total amount of mass (kg) imported remains constant across empirical, optimal, and optimum portfolios in 2020. Egypt imports 9.6 million tons of wheat, Vietnam imports 12 million tons of maize, and Saudi Arabia imports 1.5 million tons of rice.

**Table 3.** Key portfolio optimization characteristics for the major grain importers considered in this study (rounded to 3-decimal points). The mean unit value ($\$\,kg^{-1}$) matches between the empirical and optimal portfolios by definition.

| | Egypt's Wheat Imports | | |
|---|---|---|---|
| | Empirical portfolio | Optimal portfolio | Optimum portfolio |
| Panel risk | $2.54 \times 10^{-3}$ | $1.16 \times 10^{-3}$ | $5.93 \times 10^{-5}$ |
| Unit cost ($\$\,kg^{-1}$) | 0.281 | 0.281 | 0.242 |
| Diversity | 0.436 | 0.346 | 0.266 |
| | Vietnam's Maize Imports | | |
| | Empirical portfolio | Optimal portfolio | Optimum portfolio |
| Panel risk | $9.51 \times 10^{-4}$ | $6.67 \times 10^{-5}$ | $6.66 \times 10^{-5}$ |
| Unit cost ($\$\,kg^{-1}$) | 0.198 | 0.198 | 0.195 |
| Diversity | 0.499 | 0.492 | 0.491 |
| | Saudi Arabia's Rice Imports | | |
| | Empirical portfolio | Optimal portfolio | Optimum portfolio |
| Panel risk | $1.78 \times 10^{-2}$ | $3.84 \times 10^{-3}$ | $2.19 \times 10^{-3}$ |
| Unit cost ($\$\,kg^{-1}$) | 0.913 | 0.913 | 0.700 |
| Diversity | 0.651 | 0.196 | 0.175 |

risky (and more diverse) than the realized import portfolios for the year 2020. Importantly, these case studies highlight opportunities to minimize panel risk at lower cost.

The composition of total mass import (kg) across empirical, optimal, and optimum portfolios for the case study nations is shown in figure 5. The total amount of mass (kg) imported is the same across portfolios, but the composition across suppliers changes. The mass supplied by each exporter nation differs across empirical, optimal, and optimum portfolios. Notably, these portfolios are physically achievable due to the supplier mass constraint in the optimization model per importer nation (see section 2). Both optimal and optimum scenarios select the available suppliers that collectively have the lowest covariance through time (e.g. volatility in unit value is minimized). This means that these portfolios are composed of suppliers whose historic change in unit value moves in opposite directions to one another.

More detailed information on the panel risk, diversity, and cost across scenarios for the case study nations is provided in table 3. Egypt's optimal wheat portfolio reduces panel risk by 54% while also increasing diversity by 21% and keeping cost constant. More importantly, Egypt's optimum wheat portfolio reduces volatility by 98%, increases diversity by 39%, and also reduces cost by 14%. Similarly, Vietnam's optimal maize portfolio achieves 93% lower panel risk and 1.5% higher diversity than real-world trade without costing more. Vietnam's optimum maize portfolio achieves less panel risk (93% decrease) and more diversity (1.6% increase) at a lower cost (1.4% reduction). Saudi Arabia's optimal rice portfolio is 78% less risky and 70% more diverse with constant cost. Again, the optimum portfolio reduces panel risk (88% lower) and increases diversity (73% higher) at a lower cost (23% lower). These results identify that the case study nations may be able to achieve less risky and more diverse grain import portfolios at the same or lower cost. These case study findings are consistent with global results (see figure 2) in which more diverse portfolios are also less risky.

**Table 4.** Key portfolio optimization characteristics for other grain importers considered in this study (rounded to 3-decimal points). Turkey needs to pay more to achieve a more stable wheat import portfolio. The mean unit value ($\$\,\mathrm{kg}^{-1}$) matches between the empirical and optimal portfolios by definition.

| Turkey's Wheat Imports | | | |
|---|---|---|---|
| | Empirical portfolio | Optimal portfolio | Optimum portfolio |
| Panel risk | $7.68 \times 10^{-4}$ | $2.16 \times 10^{-4}$ | $1.09 \times 10^{-4}$ |
| Unit cost ($\$\,\mathrm{kg}^{-1}$) | 0.242 | 0.242 | 0.306 |
| Diversity | 0.485 | 0.358 | 0.278 |

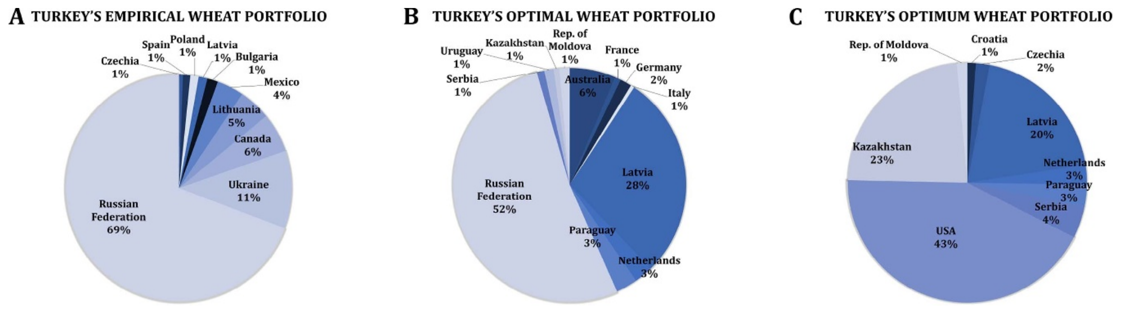


**Figure 6.** Sample supplier mass shares for (A) empirical, (B) optimal, and (C) optimum wheat imports of Turkey. To achieve more stable import portfolios, Turkey needs to spend more money.

## 4. Discussion

In this section, we further discuss our results and their policy implications. We also address the advantages and limitations of our approach.

### 4.1. Optimal and optimum grain import portfolios

In our framework, the mass supply constraint is introduced for each exporter but does not serve as a global balance. Thus, this framework is not meant to be applied to all world nations simultaneously, which would require a general equilibrium framework in which global prices would adjust with varying demands. Instead, portfolio theory is a suitable framework for small, open economies, whose portfolio adjustments would not significantly impact world prices. However, the dual objectives of grain supply affordability and stability are the most important in small, open economies, which makes our application of portfolio theory to this context suitable. Therefore, we provide individually tailored import strategies based on the historic trade relationships of these nations. Our mean-variance optimization approach could be a useful preparedness tool against potential supply disruptions, especially for low-income and generally food-insecure importers.

It is also important to note that we are not able to identify optimal or optimum portfolios that improve upon the empirical cases across all three objectives (i.e. risk, cost, and diversity of each portfolio) for all countries. This means that certain countries cannot reduce panel risk in their grain imports for the same or lower cost of imports. In other words, to reduce the riskiness of their grain import portfolios, some countries will need to spend more. This is due to each nation's grain import priorities and historic suppliers. For example, Turkey would need to spend 26% more money on wheat imports to achieve 86% more stable supplies, as seen in table 4 (also see figure 6 for Turkey's mass share distribution across available suppliers for the empirical, optimal, and optimum portfolios). This highlights that optimal and optimum scenarios with better diversity, cost, and stability can be identified for some but not all importers. However, this approach can help countries calculate how much diversifying their grain imports to reduce panel risk is likely to cost.

This distinction on Turkey's wheat imports is especially important when the positive trade-off between risk and return is considered. Due to this positive relationship, decision-makers might assume that always choosing the lowest available cost would ensure the minimum risk scenario. Further, they might switch to the next lowest cost in case a disruption occurs in their first choice supplier. However, minimum-cost portfolios do not always provide the minimum risk. If minimum cost is the priority, a new optimization model with an objective function that aims to minimize the total cost of import must be formulated and solved.

Lastly, it is important to highlight that the mean-variance optimization approach might miss some real-world details as it is based on only historical data, like other empirical approaches. In reality, altering trade relationships could involve additional costs and other socio-political issues among nations, which might make it difficult to build new trade relationships. In addition, an a-historical shock (i.e. the recent invasion of Ukraine) would not be represented in the model in its original form. For example, the optimal and optimum maize import portfolios of Vietnam suggest more reliance on both Ukraine and Russia, which has proven to be risky in light of the recent conflict. However, the mean-variance optimization is an adaptable approach and these concerns could be addressed through further modifications in the model. Through the inspiration driven by our reliability analysis of grain imports (see SI for more detail), more reliable exporter nations could be prioritized during the supplier selection, which we suggest as an important avenue for future research. Thus, a mean-variance optimization framework would be able to identify opportunities to reduce the risk of grain import portfolios (for the same cost or less) while taking other practical factors into account.

### 4.2. Policy implications

We demonstrate that portfolio theory is applicable to grain imports, which highlights the important trade-offs between risk, cost, and diversity that policy-makers may want to consider. As an example, the recent Russian invasion of Ukraine highlighted that several countries were reliant on wheat supplies from the Black Sea region (Behnassi and El Haiba 2022). Wheat from the Black Sea region is usually cheaper than wheat supplies from other regions, such as Europe or the USA (Abay *et al* 2023), which likely explains why several countries relied on Ukraine for their wheat imports. However, our findings suggest that major importers should diversify their sourcing so that they are better prepared for future crises. Importantly, our findings highlight that it may be possible for grain importers to increase their supplier diversity while also keeping costs constant (e.g. see the case of Egyptian wheat imports in section 3.3).

Another policy implication of our study is that trade can buffer shocks when the portfolio selection explicitly considers risk. For this reason, risk should be included in the policy mix to enhance the food security of importing nations. Importing nations can select their grain suppliers and the quantity to import from each supplier to minimize risk with the portfolio framework that we developed in this study. This approach will penalize countries that have historically implemented trade barriers during crises since these bans would have increased the volatility of those exporter's prices. Policy-makers often aim to discourage trade barriers during crises (Anderson 2022), since they increase the price of global supplies and tend to be contagious (Mottaleb *et al* 2022, Abay *et al* 2023). The mean-variance optimization framework penalizes countries that implement export bans by making them less desirable for importers seeking price stability. Importantly, the mean-variance optimization framework is flexible and could be adapted to include other national characteristics that policy-makers are interested in prioritizing, e.g. such as prioritizing trade with other democracies, countries in a free-trade zone, nations with high-quality infrastructure, etc.

The policy implications of our study primarily relate to trade policies, which are a complement but not a substitute for domestic food security policies (Dithmer and Abdulai 2017, Spiker *et al* 2023). Nations that are vulnerable to food price spikes may want to consider creating safety nets, as these can be effective tools to support themselves against potential food supply crises. An illustrative case is in Egypt where the government is currently expanding its existing socio-economic protection programs to shield their most vulnerable citizens against food insecurity (Belhaj *et al* 2022). However, our study is motivated by the fact that global grain markets tend to be more stable than domestic markets since they are more diverse, and global production has more adaptive capacity to withstand shocks than does any individual country (Lampietti *et al* 2011). For this reason, our study focuses on opportunities to enhance food security through the trade system, which means that domestic food security policies are outside the scope.

### 4.3. Advantages and limitations

This study enables importer nations to determine how far their current trade portfolio is from an optimal and optimum benchmark. One of the main advantages of this benchmarking approach may be for helping decision-makers determine how to reduce risk in their grain imports in a realistic way, due to the mass supply constraint on exporters and cost considerations. By comparing empirical and optimal portfolios, each nation can evaluate opportunities to adjust their trade relationships and policies to achieve less risky import portfolios at the same average unit cost. Further, importer nations can use our approach to identify if they can achieve both less risky and less costly imports, which are also more diverse, by comparing their empirical and optimum portfolios.

The main limitation of using modern portfolio theory in the context of grain trade is the lack of high-frequency historical data, when compared with financial settings. In a typical modern portfolio theory application, daily data on stock prices for a period of decades could be used to propose future investment opportunities. Unfortunately, this granularity in time records is not available for the trade statistics provided by UNCOMTRADE. Bilateral trade data is limited to the annual time step. Additionally, there are known uncertainties in the country reports that underpin the UNCOMTRADE database (refer to Chen *et al* 2022 for a discussion of outliers, missing values, and bilateral asymmetries in the UNCOMTRADE data). Uncertainties in UNCOMTRADE have primarily been noted for the material flow of goods, but we also utilize the financial value information in this study, which has less uncertainty associated with it, and, coupled with the material flow data lends credibility to our approach.

Despite these limitations, the UNCOMTRADE database is one of the most widely used and accepted databases of international trade across disciplines (Chen *et al* 2022). Thus, our use of the UNCOMTRADE database at the annual time scale is consistent with the literature, but novel in the application of modern portfolio theory to national grain imports accounts.

## 5. Conclusion and future work

This study demonstrates that modern portfolio theory can be a useful conceptual framework for understanding risks and expected returns in national grain imports. Additionally, mean-variance optimization can be used to operationalize the dual goals of cost and risk reduction in grain imports. We demonstrate that a mass balance constraint on the decision variables can be incorporated into portfolio selection analysis to simulate potential policy options. We present the optimal and optimum portfolio for several major grain importers. For some case study nations, we identify opportunities to reduce risk in grain imports while keeping the price constant or lower, such as for wheat imports in Egypt, maize imports in Vietnam, and rice imports in Saudi Arabia. Yet, some countries are not able to reduce their grain import portfolio risk without spending more money, such as wheat imports in Turkey.

Future research can build on this work, as this framework could be used by individual decision-makers interested in reducing their supply chain risks but still cognizant of costs. Optimal and optimum portfolios could be calculated for the grain import of other small open-economy nations, or for different supply chains. Future studies may want to incorporate the reliability of trade partners within the optimization model. In such cases, a minimum reliability level could be enforced during supplier selection of portfolios, enabling a deeper consideration of other socio-political factors.

## Data availability statement

All data sources are listed in the methods section of the paper and are freely available online on UNCOMTRADE's official website, https://comtrade.un.org/data.

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## Code availability statement

Code for analyzing the trade-off between risk and return of unit price and diversity of import portfolios in this study is developed in RStudio version 4.0.2. The mean-variance optimization model is formulated in Jupyter Notebook version 6.2.0 and solved by Gurobi Optimizer version 9.0.2. All codes will be made available upon reasonable request from the corresponding author.

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## References

Abay K A, Breisinger C, Glauber J, Kurdi S, Laborde D and Siddig K 2023 The Russia–Ukraine war: implications for global and regional food security and potential policy responses *Glob. Food Secur.* **36** 100675

Alvarez S, Larkin S L and Ropicki A 2017 Optimizing provision of ecosystem services using modern portfolio theory *Ecosyst. Serv.* **27** 25–37
Anderson K 2022 Trade-related food policies in a more volatile climate and trade environment *Food Policy* **109** 102253
Ando A W, Fraterrigo J, Guntenspergen G, Howlader A, Mallory M, Olker J H and Stickley S 2018 When portfolio theory can help environmental investment planning to reduce climate risk to future environmental outcomes—and when it cannot *Conserv. Lett.* **11** e12596
Ando A W and Mallory M L 2012 Optimal portfolio design to reduce climate-related conservation uncertainty in the prairie pothole region *Proc. Natl Acad. Sci.* **109** 6484–9
Behnassi M and El Haiba M 2022 Implications of the Russia–Ukraine war for global food security *Nat. Hum. Behav.* **6** 754–5
Belhaj F, Gatti R, Lederman D, Sergenti E J, Assen H, Lotfi R and Mennatallah Emam M 2022 *A New State of Mind: Greater Transparency and Accountability in the Middle East and North Africa* (The World Bank)
Beuhler M 2006 Application of modern financial portfolio theory to water resource portfolios *Water Supply* **6** 35–41
Bollino C A and Galkin P 2021 Energy security and portfolio diversification: conventional and novel perspectives *Energies* **14** 4257
Castro L M, Calvas B and Knoke T 2015 Ecuadorian banana farms should consider organic banana with low price risks in their land-use portfolios *PLoS One* **10** e0120384
Chen C *et al* 2022 Advancing un comtrade for physical trade flow analysis: review of data quality issues and solutions *Resour. Conserv. Recycl.* **186** 106526
deLlano-Paz F, Calvo-Silvosa A, Antelo S I and Soares I 2017 Energy planning and modern portfolio theory: a review *Renew. Sustain. Energy Rev.* **77** 636–51
Dithmer J and Abdulai A 2017 Does trade openness contribute to food security? A dynamic panel analysis *Food Policy* **69** 218–30
Dogan N B, Mejia A and Gomez M 2023 Cities can benefit from complex supply chains *npj Urban Sustain.* **3** 20
Donaldson D 2018 Railroads of the Raj: estimating the impact of transportation infrastructure *Am. Econ. Rev.* **108** 899–934
Donaldson G 1984 Food security and the role of the grain trade *Am. J. Agric. Econ.* **66** 188–93
Elton E J and Gruber M J 1997 Modern portfolio theory, 1950 to date *J. Bank. Finance* **21** 1743–59
FAOSTAT 2020 *Food and Agricultural Organization of the United Nations, Detailed Trade Matrix* (available at: https://fenixservices.fao.org/faostat/static/documents/TM/TM_e.pdf)
Fraser E D G, Mabee W and Figge F 2005 A framework for assessing the vulnerability of food systems to future shocks *Futures* **37** 465–79
Gani A 2017 The logistics performance effect in international trade *Asian J. Shipp. Logist.* **33** 279–88
Goddin J R 2019 Identifying supply chain risks for critical and strategic materials *Critical Materials-Underlying Causes and Sustainable Mitigation Strategies* (World Scientific Publishing Co. Pte. Ltd) pp 117–50
Gomez M, Mejia A, Ruddell B L and Rushforth R R 2021 Supply chain diversity buffers cities against food shocks *Nature* **595** 250–4
Hellegers P 2022 Food security vulnerability due to trade dependencies on Russia and Ukraine *Food Secur.* **14** 1503–10
Herman J D, Zeff H B, Reed P M and Characklis G W 2014 Beyond optimality: multistakeholder robustness tradeoffs for regional water portfolio planning under deep uncertainty *Water Resour. Res.* **50** 7692–713
Hoekstra J 2012 Improving biodiversity conservation through modern portfolio theory *Proc. Natl Acad. Sci.* **109** 6360–1
Kathiresan A, Nagai T and Haneishi Y 2020 Policy options for galvanizing Africa's rice sector against impacts of COVID-19 *World Dev.* **136** 105126
Khanal A R and Mishra A K 2017 Enhancing food security: food crop portfolio choice in response to climatic risk in India *Glob. Food Secur.* **12** 22–30
Knoke T, Paul C, Härtl F, Castro L M, Calvas B and Hildebrandt P 2015 Optimizing agricultural land-use portfolios with scarce data—a non-stochastic model *Ecol. Econ.* **120** 250–9
Koppenberg M, Bozzola M, Dalhaus T and Hirsch S 2021 Mapping potential implications of temporary COVID-19 export bans for the food supply in importing countries using precrisis trade flows *Agribusiness* **37** 25–43
Lampietti J, Larson D F, Battat M, Erekat D, De Hartog A and Michaels S 2011 *The Grain Chain: Food Security and Managing Wheat Imports in Arab Countries* (World Bank)
Markowitz H 1952 Portfolio selection *J. Finance* **7** 77–91
Markowitz H 1956 The optimization of a quadratic function subject to linear constraints *Nav. Res. Logist. Q.* **3** 111–33
Marti L, Puertas R and Garcia L 2014 The importance of the logistics performance index in international trade *Appl. Econ.* **46** 2982–92
Mottaleb K A, Kruseman G and Snapp S 2022 Potential impacts of Ukraine–Russia armed conflict on global wheat food security: a quantitative exploration *Glob. Food Secur.* **35** 100659
Paydar Z and Qureshi M 2012 Irrigation water management in uncertain conditions—application of modern portfolio theory *Agric. Water Manage.* **115** 47–54
Puma M J, Bose S, Chon S Y and Cook B I 2015 Assessing the evolving fragility of the global food system *Environ. Res. Lett.* **10** 024007
Rhoades S A 1993 The Herfindahl–Hirschman index *Fed. Res. Bull.* **79** 188
Sartori M and Schiavo S 2015 Connected we stand: a network perspective on trade and global food security *Food Policy* **57** 114–27
Seekell D *et al* 2017 Resilience in the global food system *Environ. Res. Lett.* **12** 025010
Seekell D, D'Odorico P and MacDonald G K 2018 Food, trade and the environment *Environ. Res. Lett.* **13** 100201
Spiker M L, Welling J, Hertenstein D, Mishra S, Mishra K, Hurley K M, Neff R A, Fanzo J and Lee B Y 2023 When increasing vegetable production may worsen food availability gaps: a simulation model in India *Food Policy* **116** 102416
Stringer K D 2008 Energy security: applying a portfolio approach *Balt. Secur. Def. Rev.* **10** 121–42
Trela I, Whalley J and Wigle R 1987 International trade in grains: domestic policies and trade impacts *Scand. J. Econ.* **89** 271–83
UNCOMTRADE 2020 *Trade Statistics* (available at: https://comtrade.un.org/data)
Vegh C A 2013 *Open Economy Macroeconomics in Developing Countries* (The MIT Press)
Wendling Z, Emerson J, de Sherbinin A and Esty D 2020 *Environmental Performance Index* (Yale Center for Environmental Law & Policy)
World Bank 2020a *Logistics Performance Index Aggregated Rankings Data table* (available at: https://lpi.worldbank.org/international/aggregated-ranking)
WorldBank 2020b *Worldwide Governance Indicators Databank* (available at: https://databank.worldbank.org/source/worldwide-governance-indicators)