ARTÍCULO CIENTÍFICO

Rivar
REVISTA IBEROAMERICANA DE VITICULTURA, AGROINDUSTRIA Y RURALIDAD

Editada por el Instituto de Estudios Avanzados de la Universidad de Santiago de Chile

SIMULATING GLOBAL SUPPLY CHAIN REVERBERATIONS FROM UKRAINIAN GRAIN SHIPMENT INTERRUPTIONS

Simulando las repercusiones en la cadena de suministro global de las interrupciones en el envío de granos ucranianos

Simulando as repercussões na cadeia de suministro global das interrupções no envio de graõs ucranianos

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Vol. 12, N° 34, 192-207, enero 2025
ISSN 0719-4994

Artículo de investigación
https://doi.org/10.35588/3c9rjg57

Recibido
17 de noviembre de 2023

Aceptado
29 de diciembre de 2023

Publicado
Enero de 2025

Artículo científico
This research has been funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (BR18574200 "The revival of monotowns in the conditions of the creation of New Kazakhstan on the basis of territorial marketing").

Cómo citar
Kim, S.C., Chung, J.K., Trusova, N., Akhmetova, Z. y Musayeva, N. (2025). Simulating Global Supply Chain Reverberations from Ukrainian Grain Shipment Interruptions. *RIVAR, 12*(34), 192-207, https://doi.org/10.35588/3c9rjg57

ABSTRACT
Global supply chains are of strategic importance in today's global economy. The disruption of grain supplies from Ukraine emphasises the vulnerability of these chains to unpredictable factors and justifies the relevance of the study of possible risks and consequences. The purpose of the study is to analyse the potential negative consequences that may arise due to disruptions in the supply of Ukrainian grain in the global supply chain. The research is theoretical and is based on the use of the following methods of cognition: case analysis, system and descriptive analysis, modelling, and simulation. The results indicate that disruptions in the supply of Ukrainian grain can have a serious impact on the global market and the economy of Ukraine in particular, which can lead to changes in grain prices, losses for Ukrainian agricultural enterprises, and impact on food security, both in Ukraine and in the world. This study can form the basis for building an effective strategy for minimising potential negative consequences and risks for the global market and economy of Ukraine, which is important for ensuring the sustainability and reliability of grain supply chains.

KEYWORDS
Food security, international cooperation, food crisis, risk minimisation, war.

RESUMEN
Las cadenas de suministro globales tienen una importancia estratégica en la economía global actual. La interrupción del suministro de cereales desde Ucrania subraya la vulnerabilidad de estas cadenas a factores impredecibles y justifica la relevancia del estudio de los posibles riesgos y consecuencias. El objetivo del estudio es analizar las posibles consecuencias negativas que pueden surgir debido a las interrupciones en el suministro de cereales ucranianos en la cadena de suministro mundial. La investigación es teórica y se basa en el uso de los siguientes métodos de cognición: análisis de casos, análisis descriptivo y de sistemas, modelización y simulación. Los resultados indican que las interrupciones en el suministro de cereales ucranianos pueden tener un impacto grave en el mercado global y en la economía de Ucrania en particular, lo que puede provocar cambios en los precios de los cereales, pérdidas para las empresas agrícolas ucranianas e impacto en la seguridad alimentaria, tanto en Ucrania como en el mundo. Este estudio puede formar la base para construir una estrategia eficaz para minimizar las posibles consecuencias y riesgos negativos para el mercado global y la economía de Ucrania, lo cual es importante para garantizar la sostenibilidad y confiabilidad de las cadenas de suministro de granos.

PALABRAS CLAVE
Seguridad alimentaria, cooperación internacional, crisis alimentaria, minimización de riesgos, guerra.

RESUMO
As cadeias de suministro globais tem uma importância estratégica na economia global atual. A interrupção do suministro de cereais desde Ucrânia sublinha a vulnerabilidade destas cadeias a fatores impredecíveis e justifica a relevância do estudo dos possíveis riscos e consequências. O objetivo do estudo é analizar as possíveis consequências negativas que podem surgir devido às interrupções no suministro de cereais ucranianos na cadeia de suministro mundial. A investigação é teórica e basa-se no uso dos seguintes métodos de cognição: análise de casos, análise descritivo e de sistemas, modelização e simulação. Os resultados indicam que as interrupções no suministro de cereais ucranianos podem ter um impacto grave no mercado global e na economia de Ucrânia em particular, o que pode provocar câmbios nos preços dos cereais, perdas para as empresas agrícolas ucranianas e impacto na segurança alimentária, tanto na Ucrânia como no mundo. Este estudo pode formar a base para construir uma estratégia eficaz para minimizar as possíveis consequências e riescos negativos para o mercado global e a economía de Ucrânia, o qual é importante para garantir a sostenibilidade e confiabilidade das cadeias de suministro de grãos.

PALAVRAS-CHAVE
Segurança alimentária, cooperação internacional, crise alimentária, minimização de riscos, guerra.

Introduction

The purpose of this study is to analyse the potential negative consequences that may arise due to disruptions in the supply of Ukrainian grain in the global supply chain. Specifically, the study aims to examine how interruptions to Ukraine's grain exports could impact global markets and food security, lead to economic losses for Ukraine's agricultural sector, and cause price fluctuations or supply instability. Through methods like case analysis, modelling, and simulation, the researchers seek to understand possible scenarios and outcomes, such as changes in grain prices, reductions in Ukrainian exports and farm revenues, and effects on the accessibility of food globally or in importing countries. The overarching goal is to provide data and analysis to inform strategies for mitigating risks and supporting the resilience of global grain supply networks, particularly given Ukraine's significance as a major grain exporter. The study underscores the strategic importance of supply chain stability and aims to spur further research into managing vulnerabilities in the agricultural trade system.

The global supply chain is an essential component of today's global economy, where products and resources move across international borders, connecting producers and consumers on all continents. However, this complex mechanism is quite vulnerable to negative impacts, such as supply disruptions. One of the significant difficulties is the unstable situation on global markets and external factors that can affect the supply chain. In this context, it is particularly important to investigate the possible consequences of disruptions in the supply of strategic products, including Ukrainian grain (Navrotskyi et al., 2023).

As part of their study, Ihle et al. (2022) highlight the potential consequences of a failure in the supply of Ukrainian grain, emphasizing that this can lead to inflationary, political, and social problems. The researchers suggest that reverberations in grain supplies interfere with economic processes on the global market, leading to increased inflation, disrupting food security in many countries, and causing global food problems for the population of the Global South. Thus, the significance of the study lies in the fact that Ukraine is one of the primary grain-exporting countries in the world, and interruptions in the supply of its products can have serious consequences (Trusova et al., 2023a). Many countries, especially those in Europe and Asia, depend on Ukrainian grain imports to ensure their food security and global agricultural needs. However, the modern world faces significant challenges, such as political instability, climate change, and conflicts, which can significantly affect supply chains, including transport and grain exports.

The relevance of the subject matter is based on the real risks facing the global supply chain and the Ukrainian economy. Disruptions in the supply of grain can have a serious impact on the global market and the Ukrainian economy in particular. They can lead to changes in grain prices, losses for Ukrainian agricultural enterprises, and impact on food security, both in Ukraine and in the world. Moreover, due to supply disruptions from Ukraine, other grain-exporting countries may try to increase their share in the global market, which may lead to competition and changes in the structure of the global supply chain.

Ukrainian researchers Dankevich and Naumchuk (2022), and Chobotko et al. (2022) suggest that the greatest losses are suffered by countries with economies in transition, which are the main importers of Ukrainian grain (in particular, the countries of the Middle East and North Africa), as well as Ukraine. In order to minimize the possible consequences of disruptions in

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its supply, it is necessary to understand the ways to influence this situation. This opinion is held by researchers Ben Hassen and El Bilali (2022), who emphasising that the impact of war on food security is compounded by various economic problems as well as the vulnerability and inefficiency of global food systems. Accordingly, the transition to healthy, equitable, and environmentally sustainable food systems must be strengthened through urgent and long-term reforms and policies. In addition, it is important to focus on the consequences of the problem for Ukraine, its economy, and social indicators. Ukrainian researchers Mazaraki and Melnyk (2022) discuss the need to establish internal logistics chains and mobilise resources. The vast majority of the analysed scientific papers do not study much about the importance of establishing supply chains for Ukrainian grain in the context of the continuation of the war. However, the current study includes an analysis of possible scenarios for the development of events affecting the grain situation in Ukraine.

Materials and methods

The material base of the current study is based on a multidimensional analysis and use of various sources of scientific information related to the issue of grain supply and possible consequences associated with disruptions in the supply of Ukrainian grain due to the impact of the war. Both primary and secondary sources of information are used to achieve a high level of analysis and understanding of current challenges and their possible consequences, which allows for the creation of a completer and more objective image of the situation. Thus, the study used papers by theoretical researchers from different European countries, including Israel, the Netherlands, Argentina, and Ukraine.

The material base also includes official statistical information, which is of great importance for objective analysis and comparison of data. The main information base was the official statistical information of the Ministry of Agrarian Policy and Food of Ukraine and the State Statistics Service of Ukraine. The use of such sources confirmed the results and ensured the reliability of the information used in the study. All the used data is freely available. The methodological base of the scientific work includes case analysis, system and descriptive analysis, modelling, and simulation.

Case analysis was used to compare events and situations similar to the problem analysed in the current paper. This method helped identify analogies and differences between events by looking at their consequences and how to manage them. Case analysis has become an important tool for understanding how different countries and global systems respond to similar challenges. The main comparative base was disruptions in grain supplies in Argentina in 2020 and in Ukraine in 2014.

The system analysis method allowed considering the global grain supply chain as a complex system with many interdependent components, helping to identify crucial factors and relationships that determine the stability and risks of this system. This method has contributed to an in-depth analysis of interactions between different players in the grain industry and an understanding of how these interactions can affect the consequences of supply disruptions.

Descriptive analysis allowed for the collecting and systematisation of objective information about the current state of the global supply chain, including statistics, supply dynamics, and pricing trends The method was important for creating the actual research base and confir-

ming the objectivity of the results obtained. In turn, the modeling and simulation methods were essential methods in this study.

In addition, the current study used the developed equation for determining wheat production volumes and their changes during the war (1):

$$\text{Change in production volumes} = \text{VP}(t-1) - \text{VP}(t), \qquad (1)$$

Where: VP (t-1) – volume of wheat production before the war, mln. t.; VP (t) – volume of wheat production during the war, mln. t.

The chosen methodology meets the goals of the current study, enabling a thorough investigation of the problem, considering it from different angles, and understanding its impact on the global grain supply chain and the global market.

Results and discussion

Modelling the impact of disruptions on Ukrainian grain production and exports

In the modern world, grain is one of the essential raw materials for food and economic stability in many countries. Grain supply determines the ability to provide for the country's population and carry out international trade in agricultural products. Ukraine, which is one of the world leaders in grain production and export, plays a significant role in global grain supply. However, recent events related to geopolitical conflicts (including the beginning of Russia's full-scale military invasion of Ukraine in February 2022) and other factors have caused disruptions in the supply of Ukrainian grain, which causes serious consequences both for Ukraine and for the global grain market (Chobotko et al., 2022). In addition, these disruptions can serve as an object of research to analyze the impact of such factors on the global supply chain of grain.

Thus, it is important to understand that the smooth operation of the supply chain of grain plays a crucial role in the global agricultural sector and has a significant impact on the socio-economic well-being of the world. Ukraine is one of the largest grain-exporting countries in the world and provides an important component of the global food chain. It supplies a significant amount of grain to world markets, which is crucial for food safety and economic development in many countries (Mottaleb et al., 2022). Uninterrupted grain supplies from Ukraine contribute to maintaining stable grain prices, which is a critical factor in avoiding hunger and social tension. Global markets can be very sensitive to even minor supply disruptions from such a large supplier as Ukraine.

The importance of Ukraine in the world of grains lies in its ability to produce high-quality grain and ensure its availability to importers, which allows for a variety of food products and promotes competitiveness in global markets. For example, according to official data from the World Bank, over the past five years, Ukraine has always been among the top ten wheat-producing countries (Figure 1).

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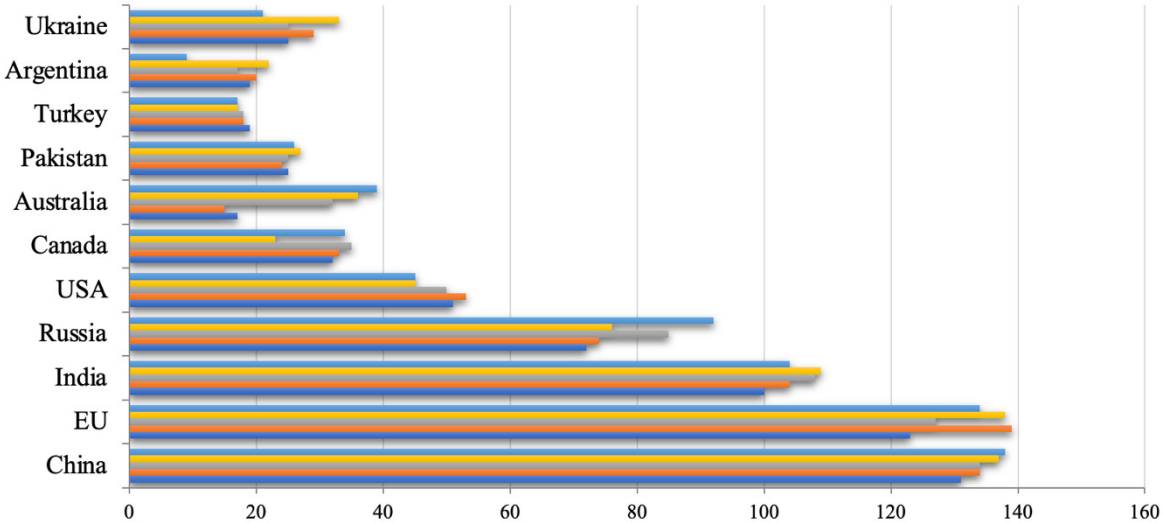
Figure 1. Top ten wheat-producing countries in 2018-2023 (in mln. t.)
Figura 1. Los diez principales países productores de trigo en 2018-2023 (en millones de toneladas)

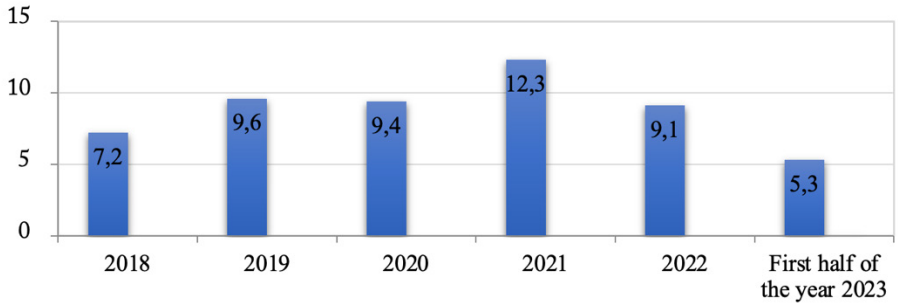


	China	EU	India	Russia	USA	Canada	Australia	Pakistan	Turkey	Argentina	Ukraine
2022/2023	138	134	104	92	45	34	39	26	17	9	21
2021/2022	137	138	109	76	45	23	36	27	17	22	33
2020/2021	134	127	108	85	50	35	32	25	18	17	25
2019/2020	134	139	104	74	53	33	15	24	18	20	29
2018/2019	131	123	100	72	51	32	17	25	19	19	25

Source: own elaboration. Fuente: elaboración propia.

These statistics show that Ukraine has quite stable indicators of wheat production over the past five years. The lowest result occurred in the period 2022-2023, which was conditioned by military events on the territory of Ukraine. Moreover, due to Russian military aggression, there is a decrease in the total volume of agricultural production in Ukraine due to the occupation of part of Ukrainian territories, mining of fields, and destruction of agricultural machinery (Trusova et al., 2023b). The commodity structure of Ukraine's foreign trade, according to the indicator "Grain", for the last five years is shown in Figure 2.

Figure 2. Commodity structure of Ukraine's foreign trade, according to the indicator "Grain" (in billion USD)
Figura 2. Estructura de productos básicos del comercio exterior de Ucrania, según el indicador "cereales" (en miles de millones de dólares)

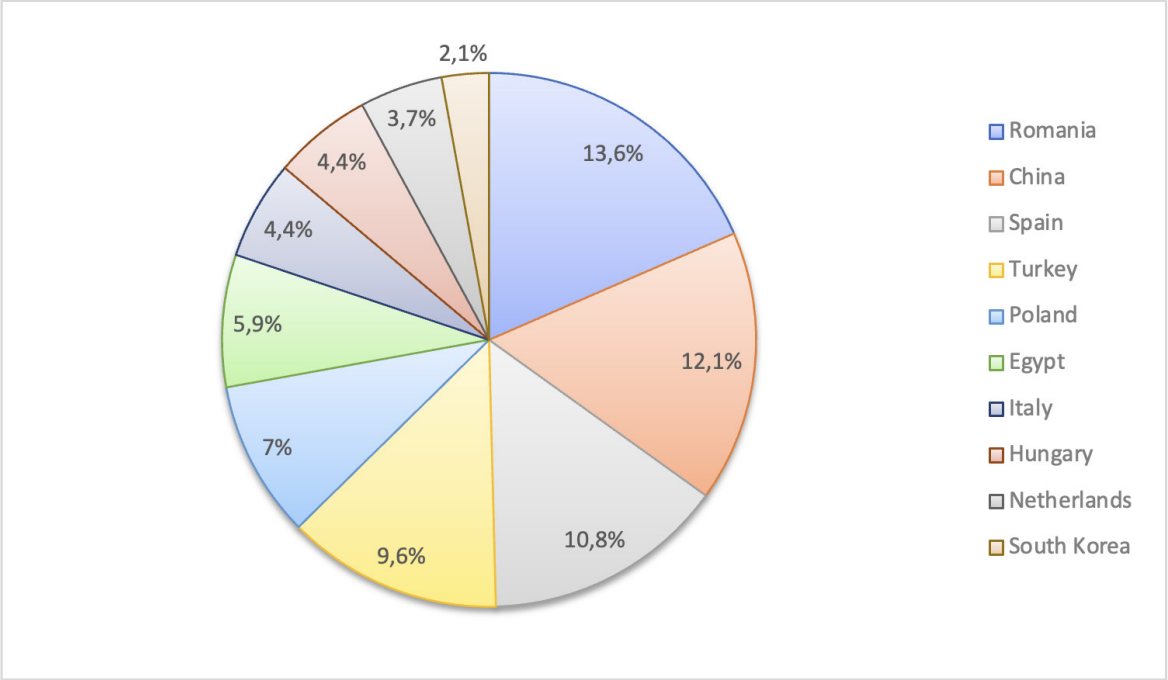


Source: own elaboration. Fuente: elaboración propia.

Broader market impacts and changes in global food security

The most profitable year for grain sales was 2021. In 2022, profit from the sale of grain crops decreased by USD 3.2 billion due to the outbreak of a full-scale war. This represents a 26% drop in this indicator. The countries that were the largest importers of Ukrainian grain in 2022 (Figure 3).

Figure 3. Ukrainian grain export distribution in 2022
Figura 3. Distribución de las exportaciones ucranianas de cereales en 2022



Source/fuente: Alexander et al. (2022).

This shows that, despite the war, Ukrainian grain does not lose demand on the global market. Grain crops are exported to Europe, Asia, and Africa. This situation shows the high potential of Ukraine to influence the global food situation through changes in its production and export of grain crops. To understand the role of Ukraine in the grain industry, it is necessary to analyse the events of 2014. At that time, the beginning of the war and subsequent events in Ukraine affected the supply chain of grain and had significant consequences for both the Ukrainian and global food systems (Alexander et al., 2022). As a result of the decrease in grain production in Ukraine and interruptions in its supply to global markets, there was a noticeable difference in instability and rising grain prices.

As a result, disruptions in the supply of Ukrainian grain have severely affected the global food system. Ukraine was one of the central players in the global grain market, and its unstable supply led to shortages and rising food prices in many countries. This particularly affected countries that were dependent on grain imports and caused economic and social problems. Moreover, disruptions in the supply of grain crops from Ukraine have led to changes in the structure of the global grain market (Penkova et al., 2020). Other major grain ex-

porting countries like the United States, Canada, France, Australia, Russia, and Brazil began to try to increase their share in the global market, which led to increased competition and changes in the structure of the global supply chain for grain (Lin et al., 2023). Consequently, disruptions in the supply of Ukrainian grain due to the Russian-Ukrainian war in 2022 had a significant impact on the global food system, causing instability, rising prices, and changes in the market structure. This highlights the importance of developing a stable and reliable supply chain in today's wartime environment.

As noted above, with the beginning of Russia's military aggression against Ukraine in 2014, other grain-exporting countries began to increase their production and sales volumes. However, some countries have faced unpredictable production disruptions caused by natural disasters. Thus, in 2020, Argentina faced similar problems due to favourable climatic conditions and increased demand for grain (Siegel, 2021). This led to higher prices and additional difficulties for grain importers. An important problem that year was the weather conditions, in particular the drought, which seriously undermined yields. This negative natural phenomenon has led to a significant decrease in the production of cereals, including soybeans and corn, which are of great importance in the global market. At that time, the Argentine authorities imposed temporary restrictions on grain exports aimed at ensuring domestic food security and stable prices on the internal market. This strategy led to restrictions on access to Argentine grain on the global market, which caused tension, increased instability, and price fluctuations (Cano and Gentili, 2023).

It is important to understand that the war in Ukraine is a critical factor in influencing the global grain market, and even if it is possible to increase production in other countries to level the losses of Ukrainian grain, this does not exclude the occurrence of crises related to weather conditions, as the example of Argentina in 2020 showed. Thus, ensuring an uninterrupted supply chain is an important area of work for the international community (Tymchuk et al., 2021). Thus, it is necessary to clearly understand the need to identify possible threats to the countries of the world and, directly, to Ukraine related to disruptions in grain supplies. This is an urgent and crucial task, as this area is of utmost importance for the socio-economic well-being of not only individual countries but also the global food system (Sirenko and Mikuliak, 2022).

Importance of supply chain resilience and international cooperation

Since grain plays a pivotal role in ensuring global food security, millions of people depend on access to sufficient quantities and quality of grain. Supply disruptions can lead to price instability and limited access to food resources, posing a threat to food security. Moreover, the grain industry is a vital sector for the economies of many countries, including Ukraine. Supply disruptions can lead to lower export revenues, losses for agricultural sectors, and general economic instability. It is important to consider that many grain regions of the world are located in zones of geopolitical conflict (Skydan et al., 2023). Geopolitical conflicts in the Middle East, North Africa, Venezuela, Sub-Saharan Africa, and Afghanistan have resulted in significant disruptions to grain production, supply chains and food security. Increased conflicts and instability can lead to an increased risk of supply disruptions and threats to supply security. As noted earlier, climate changes such as heat, droughts, and floods can also significantly affect grain yields in different regions of the world. Projected climate changes increase the risk of supply stability.

The modern global food system is characterised by the high interdependence of countries in the field of grain supplies. Therefore, supply disruptions in one country may have a further resonance in others, which highlights the need for risk analysis and minimisation (Liu et al., 2023). All these aspects emphasise the need to identify possible threats to the countries of the world and Ukraine associated with disruptions in grain supplies. Such analysis will help develop strategies to minimise risks and ensure the stability of both national and global food systems. According to this, as part of the current study, a model was developed that describes the dynamics of the global grain supply chain and allows modelling various scenarios of supply disruptions. The evaluation model is as follows in Table 1.

Table 1. Evaluation Model Variables
Tabla 1. Variables del modelo de evaluación

No.	Evaluation model	Description
1	Time variables	Start date and time of the simulation
		Simulation period (e.g., months or years)
2	Grain changes	Grain production volumes in Ukraine (annual or monthly)
		Grain export volumes from Ukraine
		Grain prices on the global market
3	Variable supply chains	Costs of grain production and supply
		Time of grain delivery from Ukraine to other countries
		Influence of political, economic, and other factors on the supply chain
4	Risk and uncertainty variables	Probability of supply disruptions (e.g., military events or natural disasters)
		The amount of possible losses in case of supply disruptions
		Scenarios of interaction with other countries and participants in the supply chain

Source: own elaboration. Fuente: elaboración propia.

The current model allows for the simulation and prediction of the possible consequences of failures in the supply of Ukrainian grain, considering various factors of influence. According to the needs put forward, the data in the model can be edited. The current study predicts the possible consequences of the global supply chain, including interruptions influenced by the Russian-Ukrainian war. Output parameters: Pre-war wheat production: 33 mln. t.; Wheat production during the war: 21 mln. t.

The impact of military operations on the volume of grain production, storage, and transportation is extremely negative: theft of grain reserves by Russian troops, mining of fields, occupation of parts of territories. The impact of the war on the supply chain was negative: the lack of a stable grain export corridor prevented the shipment of Ukrainian grain by Russia.

Scenario 1. Continuation of active hostilities and failure to reach agreements on a stable corridor for exports (active hostilities on the territory of Ukraine continue; it was not possible to reach agreements on providing a stable corridor for the export of Ukrainian grain; the infrastructure of the supply chain is being destroyed; access to certain territories is restricted due to active hostilities).

Scenario 2. Cessation of hostilities, Ukraine's victory, territorial reintegration, and restoration of logistics infrastructure (the fighting ended with Ukraine's victory, Russia's complete surrender, Ukraine's return of the territories of 1991, return of temporarily occupied territories that are part of the agricultural sector, supply chain infrastructure needs to be restored

$$\text{Change in production volumes} = 33 - 21 = 12 \text{ mln. t.} \quad (2)$$

and repaired, fields need to be cleared for safe agricultural production, Ukraine receives international support to restore the supply corridor). Calculation of wheat production volumes and their changes during the war (2):

Determining the impact of military operations on the supply chain and grain exports can have various aspects, such as reducing the number of available routes for export, additional costs for ensuring cargo security, and delays in transportation through territories under the control of the occupation forces. Thus, the study considered two possible scenarios for a possible solution to the problem in the supply of Ukrainian grain, which are shown in Table 2.

Table 2. Current mechanisms for the protection of cultural heritage in Europe
Tabla 2. Mecanismos actuales para la protección del patrimonio cultural en Europa

Results	Scenario 1	Scenario 2
Changes in production volumes	Reduction of wheat production in Ukraine	Return of wheat production volumes close to previous levels
Export losses	Significant losses in Ukrainian grain exports	Reducing losses
Changes in grain safety and transportation costs	Increased costs for grain safety and transportation due to the difficult situation in the territory	Conditions for grain safety and transportation have been improved, but the cost of infrastructure repairs and field clearance may increase
Supply chain delays and uncertainties	Supply chain delays and uncertainties	Reduction of supply chain delays and uncertainty
Risk and profit volumes	Increased risk of losses and reduced profit	Reduction of risks and increase in profits
Possible changes in the global market	Changes in the global grain market	Ukraine can restore its level of competitiveness in the global market
Stability and level of food security	Increase of instability and decline in food security in some countries	Restoration of production and reduction of instability, which will lead to improved food security

Source: own elaboration. Fuente: elaboración propia.

These two scenarios illustrate possible scenarios and their impact on the supply chain of Ukrainian grain. Considering these scenarios, it is possible to simulate and assess the consequences for grain production and supply under various conditions.

In recent years, the world has witnessed significant changes in global grain supplies, especially in the context of the impact of Ukrainian disruptions in the supply of this strategically important agricultural product. According to current trends in the global economy, society is increasingly dependent on the stable and efficient functioning of supply chains. Grain suppliers and consumers from all over the world are counting on the uninterrupted supply of this important product. Accordingly, the importance of careful analysis and modeling of the possible consequences in the supply of grain from Ukraine is becoming essential in the modern global economy.

Modelling and scenario outcomes

Monitoring of the grain market and its supply chain is becoming increasingly relevant due to numerous factors, such as geopolitical conflicts, climate change, and growing demand for food. Findings are important for understanding possible challenges and risks in the global supply chain of grain and for developing strategies to minimize possible negative impacts.

Comparing the above with the results of the current study, there is a general emphasis on the issue of weak links in the supply chains of Ukrainian grain and their vulnerability. Both studies recognise that such weaknesses can be used by Russia as an instrument of aggression to achieve its political and economic goals. However, the current study adds an additional dimension to this problem, namely, focusing on the economic and social consequences of such supply chain disruption. It is noted that not only Ukraine but also other countries and the global grain market may feel the consequences of such disruptions. Rising grain and food prices can be a serious problem for consumers, especially those living in countries with high levels of poverty (Penkova and Kharenko, 2023).

European researchers Berkhout et al. (2022) suggest that European countries are protected from the food crisis, which may occur due to a violation of the supply chain of Ukrainian grain. However, the researchers believe that the main problem now concerns access to food, which is a consequence of rising prices for these products. This is especially true for people in poorer countries, some of whom spend more than half of their income on food. Researchers note that the current situation, which is a consequence of the war, is caused by a number of logistical problems. Now, the war in Ukraine creates problems with the supply of raw materials, as transport supply chains to and from Ukraine are disrupted or impossible. Therefore, companies are looking for alternative suppliers, which creates additional pressure on prices in the grain market. The study also highlights the existence of logistical problems that have arisen due to the war and illegal actions on the part of the aggressor country. The results obtained draw attention to the economic and social consequences of supply interruptions involving Ukrainian grain. It is determined that a decrease in grain exports from Ukraine can lead to an increase in food prices on the global market, which can become a problem for people in poorer countries who already face high food costs (these include countries in Africa, Asia, and some European countries). Thus, the current study highlights the importance of achieving supply chain stability to ensure access to food for the entire world's population.

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Researchers Srai et al. (2023) substantiate the need to develop a structure that combines institutional changes in trade policy with the reconfiguration of the supply network for grain. The researchers suggest that the need to develop a stable supply chain requires new investments and the proactive construction of international partnerships. It is important to understand that Russia, for example, was the main supplier of energy for a number of European countries, and Ukraine was a significant supplier of grain for regions such as the Middle East and Africa. But other countries, such as China, under the influence of the war in Ukraine and the emergence of supply problems, have changed their position, which has led to changes not only in Europe and Africa, but also in global supply chains. The researchers emphasise that this model change will require significant reconfiguration in the short, medium, and long term. It is important to understand that the problem of supply interruptions caused by the war involving Ukrainian grain is almost unpredictable.

However, the study considered two main scenarios for the development of further actions and possible consequences. According to the first scenario, where active military operations on the territory of Ukraine continue, an even greater increase in grain prices on the global market will be recorded, as will a decrease in exports from Ukraine. This led to difficulties for countries that were previously dependent on Ukrainian grain and prompted them to look for alternative sources of supply. For example, China is growing as a key player in the global grain market, changing the geographical structure of supplies. In the second scenario, where the conflict ends with the victory of Ukraine and the restoration of the supply chain, there are positive consequences for the global grain market. Production and export volumes are recovering, prices are stabilising, and the market is once again predictable. However, it is important to consider that the restoration of the supply chain requires investment and reconfiguration. Logistics infrastructure, agricultural land, and equipment for their processing require repair and clearance. Notably, the process of restoring the entire production structure of Ukraine can take a long time, so that is why Ukraine needs international support.

Ripple effects for global food security

These results confirm the statement of Srai et al. (2023) on the importance of developing stable supply chains and new investments in the context of geopolitical and logistical risks. In turn, the simulations highlight the need for a rapid response to changes in grain supply chains and the active development of international partnerships to ensure the stability and reliability of the global agricultural market in conditions of uncertainty and conflict. Thus, the study indicates a greater vulnerability of the agricultural sector and the global economy to such crisis situations. In particular, the decline in grain exports from Ukraine leads to an increase in prices on the global market and affects the availability of food products for consumers. The study also highlighted the need to develop sustainable and resilient risk management mechanisms in the agricultural sector. Ultimately, the importance of cooperation between countries and international organisations in managing crisis situations in the agricultural sector was highlighted. The provision of support and joint responses to such challenges can help reduce the impact of supply disruptions on global stability and economic development in the grain industry.

This study thus makes an important contribution by modelling the potential impact of trade disruptions caused by the war between Russia and Ukraine on grain availability and prices. By quantifying the potential losses to Ukrainian exports, production and agricultural sec-

tor incomes, and projecting the growth and volatility of grain prices on world markets, the analysis begins to fill a gap in the literature on realistic scenarios and the impact of prolonged supply chain constraints associated with this crisis and war. While previous work has focused on food security risks or supply chain shocks, without focusing modelling directly on cereals or the impact of the war in Ukraine, this study provides detailed evidence of how geopolitical fault lines can cascade through trade networks, undermining stability in intertwined food systems around the world. The serious findings of the forecast underscore the urgency of policy measures and cooperation agreements to ensure food availability in times of conflict through channels such as humanitarian corridors, strategic buffer stocks, and sharing of responsibilities between countries to mitigate the impact of the crisis.

Conclusions

As part of the current study, an analysis of the possible consequences of disruptions in the supply of Ukrainian grain for the global supply chain was carried out. The findings demonstrate how vulnerabilities in supply chains and trade networks can cascade into price spikes, localized shortages, and food access issues worldwide. This underscores the need for policies and agreements that mitigate trade disruptions and ensure supply chain resilience, even during conflicts. A decrease in grain exports from Ukraine may lead to higher prices on the global market, which, in turn, will affect the cost of food and consumer opportunities of the population. Moreover, as part of the study, it was found that disruptions in the supply of grain will affect the socio-economic well-being of Ukraine itself. The agricultural sector is one of the key sectors of the Ukrainian economy, and any disruptions in its functioning will have serious consequences for the employment and income of the population. Moreover, the destruction of infrastructure by the occupation forces, and losses from the theft of grain reserves led to significant economic losses.

In the context of the global supply chain, the study highlighted the importance of developing stable and reliable risk management mechanisms in the agricultural sector. Given the possibility of similar situations in the future due to various factors, including conflicts and natural disasters, the study highlighted the need to develop alternative supply routes and diversify grain sources for global markets. In addition, the study identifies the importance of international cooperation and support in situations such as the one under analysis. The international community should work to develop mechanisms aimed at preventing possible disruptions in the supply of strategic food resources, as well as at rebuilding and supporting countries affected by conflicts and crises.

This analysis centered on grain but outcomes may differ across other crops. More research could help parameterize models with finer-grained data. The study focused heavily on Ukraine's exports, but assessing production and demand changes across importing countries could also illuminate food access issues. Additionally, explicitly modeling impacts beyond crop outputs, like fertilizer availability and farming investments compromised by conflict, could bolster frameworks.

The study results indicate the importance of further research in the field of global grain supply chains, in particular, the need for an in-depth analysis of the impact of geopolitical and environmental factors on the sustainability of these chains, the development of strategies for adapting to unpredictable conditions, integration of the latest technologies for monito-

RIVAR I Volumen 12, n° 34, 2024: 192-207 • ISSN online 0719-4994
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ring and managing risks, and cooperation between countries and international organisations in order to ensure the stability of the global agricultural market and food security. In general, the current study provides an important contribution to understanding the possible consequences of disruptions in the supply of Ukrainian grain for the world economy and emphasises the need to develop sustainable and resilient risk management mechanisms in the agricultural sector.

Several fruitful research directions emerge from this study. First, applying similar simulation models to other major food exporters facing climate or conflict risks could reveal regional and global impact patterns. Second, dynamic modeling that captures decision-making by governments, commodity traders, and consumers in response to supply volatility could sharpen insights into market behaviors. Examining ripple effects across multiple crops would also better represent realities facing food systems. Finally, coupling trade disruption assessments with evaluations of policy interventions like strategic reserves, trade agreements, or social safety net programs could guide initiatives to safeguard food security when shocks emerge. Representing these complex systems requires advanced modeling but offers significant potential to manage risks. The scenario modelling provides frameworks that researchers can build upon to analyse risks from future shocks to agricultural outputs and trade. As climate change and resource constraints loom, modelling the systemic impacts of supply volatility is increasingly vital. For policymakers, this research reinforces the importance of strategic food reserves, diversified import arrangements, and support programs to shield vulnerable populations when prices or availability fluctuate. Prioritizing stability in grain trade must be part of food security agendas.

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