Economics and Business Management

16(4), 9-23
Journal homepage: https://economicscience.com.ua/en
Received: 07.07.2025 Revised: 24.10.2025 Accepted: 27.11.2025

UDC 338.439:551.58:327(4)
DOI: 10.31548/economics/4.2025.09

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The impact of global climate change and Russian aggression in Ukraine on global food security

Abstract. The issue of food security has become particularly relevant in the context of intensifying climate change and geopolitical threats, in particular the war in Ukraine. The aim of the study was to determine the impact of climate change and Russian aggression in Ukraine on the functioning of global agri-food systems. The main focus was on analysing the impact of extreme weather events, water shortages, changes in precipitation patterns and military actions on crop yields, food quality and value, and the functioning of supply chains. The methodological basis of the study was a combination of quantitative analysis of statistical data with qualitative analysis of regional adaptation strategies and socio-economic consequences. The results indicated a high vulnerability of Southern and Central Europe. A decline in wheat, maize and barley yields has been recorded in Southern and Central Europe, while in Northern Europe there has been an increase due to the lengthening of the growing season. In addition, a deterioration in the nutritional value of products has been identified due to a decrease in micronutrient content. The analysis confirmed the effectiveness of climate-resilient technologies, precision farming and community participation in adaptation processes. Special attention was paid to the impact of the full-scale war in Ukraine on food security. It led to a reduction in cultivated areas, loss of production capacity, disruption of logistics and exports of agricultural products, a sharp rise in food prices and social tensions in importing countries. The summary of the results emphasised the need for integrated and regionalised approaches to food security policy in the context of increased climate shocks and other risks. At the same time, the introduction of climate-resilient technologies, diversification of supply and strengthening of international cooperation are critical for the formation of sustainable agri-food systems of the future. The practical significance of the study was to develop scientifically sound approaches to adapting the agricultural sector to climate change and the impact of wars

Keywords: agriculture; adaptation strategies; agricultural sector resilience; post-war recovery; hidden hunger

Suggested Citation:
Tymchak, V. (2025). The impact of global climate change and russian aggression in Ukraine on global food security. *Economics and Business Management,* 16(4), 9-23. doi: 10.31548/economics/4.2025.09.

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INTRODUCTION

Climate change and military factors are the main threats affecting ecosystems, economic stability and human well-being on a global scale. The agricultural sector is the foundation of global food security, which is particularly vulnerable due to its dependence on climatic conditions such as temperature, precipitation and the frequency of extreme weather events. In the European Union (EU), the negative effects of climate change are manifested through regional differences, creating an uneven distribution of risks that requires more in-depth analysis. This study is relevant due to the growing threats to food security, increasing economic instability, and the need to integrate climatic and geopolitical factors into the sustainable development policies of European countries and the world.

H. Fraga *et al*. (2012) argued that Southern Europe (Spain, Italy, Greece) suffers from prolonged droughts, soil degradation and water shortages, while Northern Europe (Sweden, Finland, Denmark) faces excessive humidity, shifts in growing seasons and the spread of new phytopathogens in these areas. An analysis of scientific papers demonstrates active research into the impact of climate change on agricultural production, indicating that this is a fairly large-scale problem. According to a report by the Food and Agriculture Organization of the United Nations (2021), in some regions, changes in climatic factors have caused a 20-25% over the last two decades, from 2000 to 2020, exacerbating the food crisis and intensifying migration processes. In South Asia, water shortages and rising temperatures threaten rice production, which is the staple food for billions of people, creating risks of famine and economic instability. Unlike these regions, Europe has the infrastructure and resources to adapt to climate change and other challenges, but its food systems are also becoming increasingly vulnerable due to market globalisation and dependence on imports of raw materials, particularly cereals and oilseeds. The Organisation for Economic Co-operation and Development (2023) noted that climate shocks in other parts of the world, such as droughts in North America or floods in Australia, can cause price fluctuations in European markets, thereby worsening access to food for vulnerable populations.

Recent studies by Ukrainian scientists are mainly related to the impact of military operations on the Ukrainian economy, in particular the agricultural sector and logistics chains. P. Martyshev *et al.* (2023) found that military action in Ukraine has a negative impact on agriculture, significantly undermining food security in Ukraine. A. Skrypnyk *et al.* (2021) examined the impact of climate change and military action on Ukraine's agricultural sector. According to estimates by the Intergovernmental Panel on Climate Change (2022), even under a moderate warming scenario (+1.5°C), the yield of major crops in Europe could decline by 10-20% by 2050, posing a threat to both domestic food balances and global markets. In addition, climate change also affects the quality of agricultural products. Research by D.E. Medek *et al.* (2021) and I. Al-Hadeethi *et al.* (2019) showed that negative climate change reduces the content of micronutrients (protein, iron, zinc), which increases the risk of "hidden hunger" – a deficiency of nutrients that has long-term negative consequences for the health and nutrition of the population.

The global scientific community is actively researching the impact of climate change on agricultural production, but most studies focus on global trends or individual regional cases, while a comprehensive analysis of the interrelationships between climatic, agricultural and social factors within the EU remains understudied. Some studies, in particular A. Mirzabaev *et al.* (2023) and the Intergovernmental Panel on Climate Change (2022), highlight global challenges to food security but do not take into account the specificities of European agroecosystems. At the same time, the European Environment Agency (2024) focuses on regional aspects but rarely integrates socio-economic and other factors, such as the war in Ukraine, which has significantly affected European food chains. Such studies require an interdisciplinary approach that combines a range of disciplines (climatology, agronomy, economics and sociology). This approach is necessary to understand the complex dynamics of food security in the EU.

In the context of the implementation of the European Green Deal (European Commission, 2019) and the "Farm to Fork" strategy (European Commission, 2020), research into adaptation solutions is becoming particularly relevant in practical terms. These initiatives aim to create sustainable and environmentally safe food systems, but they also face challenges such as the high cost of transitioning to organic farming, potential temporary productivity losses, and uneven access to financing for small farms. The work of M. Zurek *et al.* (2022) has shown that requirements to reduce pesticide use by 50% by 2030 may complicate the fight against new phytopathogens in Northern Europe, while in Southern Europe, moisture shortages limit the scaling up of irrigation systems. At the same time, these strategies open up opportunities for the introduction of innovative technologies that can increase the resilience of the agricultural sector.

The main challenge facing agricultural specialists is ensuring food security in the context of climate change. It is these changes that affect food security through reduced yields, deteriorating product quality and rising prices. In particular, a report by the Food and Agriculture Organization of the United Nations (2021) showed that rising temperatures and rainfall deficits between 2000 and 2020 reduced rice production in South Asia by 15%, creating risks for food security. In addition, the war in Ukraine has a significant impact on food security. Thus, the aim of this study was to analyse the impact of climatic factors and the war in Ukraine on food security.

MATERIALS AND METHODS

This study covered the period from 2015 to 2024 (within this period, grain exports in 2021 and 2022 were also analysed, and the impact of hostilities on grain exports was analysed) in comparison with the period 2010-2014. This period was chosen because from 2010 to 2014 there was no significant increase in negative climate change that could have caused catastrophic consequences. However, from 2015 to 2024, the climate situation deteriorated under the influence of a number of factors, both natural (droughts, heavy rainfall, dry winds) and anthropogenic (military operations, etc.). The study used a comprehensive methodological approach that combined analysis of literary sources, statistical modelling, and qualitative analysis of regional characteristics. The methodology was designed to ensure that other scientists could replicate the study using similar materials and methods. The study was conducted in several stages aimed at obtaining reliable scientific results.

Stage 1. Analysis of literary sources. At the first stage, a systematic review of scientific publications on the impact of climate change and other factors on the agricultural sector and food security was conducted. In particular, the work of P. Lamichhane *et al.* (2022), which proposed the concept of adaptive agricultural risk management; the study by the Intergovernmental Panel on Climate Change (2022), which identified key global risks to the food system; and the report by the Organisation for Economic Co-operation and Development (2023), which highlighted the impact of the war in Ukraine on global food chains. Sources were selected based on criteria of relevance, scientific reliability and relevance to the topic. This stage allowed to identify the main climate risks, regional characteristics and gaps in current research.

Stage 2. Sample formation and experimental base. The study covered the most developed countries of the European Union, with an emphasis on regional differences between southern (Spain, Italy, Greece), central (Germany, France, Poland) and northern (Sweden, Finland, Denmark) countries. It also included countries in Asia and Africa, namely Bangladesh and Mozambique, given their vulnerability to climate risks and their role in agri-food chains. These countries were included in the sample for a comparative analysis of the effectiveness of adaptation strategies under different climatic, social and institutional conditions. The sources of information are standardised according to the methodologies of CARE International (2009) and the Intergovernmental Panel on Climate Change (2022), which ensures the comparability of data and the relevance of conclusions. The sample was formed based on the following criteria: 1) the level of dependence of the gross domestic product (GDP) structure on agriculture;

2) vulnerability to climate change (droughts, floods, soil erosion); 3) availability of data on the yield of key crops (wheat, maize, barley) for 2015-2024. The experimental base included statistical data from the Food and Agriculture Organization (2024) and the European Environment Agency (2024).

Stage 3. Research methods. To assess the impact of climate change on food security, methods such as statistical, comparative and qualitative analysis were used. Statistical analysis: regression analysis was used to assess the dependence of crop yields on climate variables (temperature, precipitation, frequency of extreme weather events). Comparative analysis: a comparison of agricultural productivity in different regions of the European Union was carried out to identify regional differences in vulnerability to climate change. Qualitative analysis: content analysis was used to assess the adaptation strategies described in the literature and their effectiveness in the context of EU countries. This included an analysis of reports on the implementation of climate-resilient crop varieties, irrigation systems and digital technologies (International Fund for Agricultural Development, 2023; Balasundram *et al.,* 2023; Ukraine rapid damage and needs assessment..., 2023). The analysis of the impact of the war in Ukraine was carried out using a counterfactual approach to assess losses in cropland, export potential and food inflation.

Stage 4. Assessment of socio-economic consequences. To analyse the impact on food security, the author used a vulnerability assessment method that took into account the availability of products, their quality and price stability. Data on food prices and availability for vulnerable groups were collected from Eurostat (n.d.) and the State Statistics Service of Ukraine (2024).

The choice of methods was dictated by the need for a comprehensive analysis of a multifaceted problem. Statistical and comparative analyses provide a quantitative assessment of the impact of climate change and other factors, while qualitative analysis allows for institutional and social aspects to be taken into account. The use of open data from the FAO (Food and Agriculture Organization, 2024) and the EEA (European Environment Agency, 2024) guarantees the reliability and reproducibility of the results. A comprehensive approach to sample selection made it possible to cover the diversity of climatic and agricultural conditions in Europe and the world, ensuring the representativeness of this study.

RESULTS AND DISCUSSION

Climate change is one of the key factors affecting global food security, altering the volume and stability of crop production in different regions of the world. Rising average annual temperatures and more frequent extreme weather events, such as droughts and floods, are leading to lower yields in tropical and Mediterranean regions, while at the same time partially increasing productivity in northern latitudes (Intergovernmental Panel on Climate Change, 2022; Food and Agriculture Organization of the United Nations, 2024). Along with changes in quantitative indicators, there is a deterioration in product quality due to a decrease in protein and micronutrient content and an increase in the risk of mycotoxins (Medek *et al*., 2021). In addition to purely climatic risks, military conflicts also have a negative impact on food security. Such changes put additional pressure on food systems, increase price volatility in global markets and exacerbate inequalities in access to quality food in low-income countries. In this context, it is particularly important to develop and implement adaptation strategies that can minimise the negative impact of climate factors and ensure the stability of agricultural production at both the global and regional levels.

The author's research revealed regional differences in the impact of climate change and the war in Ukraine on food security in Europe. The study was based on an analysis of the impact of military action and climate change on the yield of key crops (wheat, maize, barley), product quality and the effectiveness of adaptation strategies in EU countries for 2015-2024. Approaches developed by scientists (Lobell *et al*., 2011; Trnka *et al.,* 2019) were used to process the data obtained, in particular regression analysis and scenario modelling based on climate scenarios RCP 4.5 and RCP 8.5. In addition, data was collected on how climate shocks affect the yield of major crops (Table 1).

Table 1. Changes in the yield of key crops in EU regions (2015-2024, % compared to 2010-2014)

Region	Wheat	Maize	Barley
Southern Europe average for 2015-2024 (Spain, Italy, Greece)	-15.3 (±2.1)	-12.4 (±1.9)	-10.8 (±1.7)
Southern Europe (Spain, Italy, Greece) for 2022	-18.5	-15.2	-13.1
Central and Eastern Europe average for 2015-2024 (Germany, France, Poland)	-6.5 (±1.4)	-8.7 (±1.8)	-4.2 (±1.3)
Central and Eastern Europe for 2022 (Germany, France, Poland)	-9.1	-11.3	-6.5
Northern Europe average for 2015-2024 (Sweden, Finland, Denmark)	+3.1 (±1.2)	+4.8 (±1.5)	+6.2 (±1.5)
Northern Europe for 2022 (Sweden, Finland, Denmark)	+2.8	+4.2	+5.5

Source: compiled by the author based on research by the Food and Agriculture Organization of the United Nations (2024), Copernicus Climate Change Service (n.d.)

Analysis of Table 1 showed that in Southern Europe, wheat yields decreased by 18.5% (±2.1%, 95% confidence interval) in 2022 due to droughts and water shortages compared to the average yield for the period 2010-2014. The main reasons for this were intense droughts and water shortages, which limited the availability of soil moisture, as well as high temperatures during the heading and grain filling phases, which caused a decrease in crop weight and quality. In Central and Eastern Europe, maize yields fell by 11.3% (±1.8%) in 2022 due to irregular rainfall and frosts compared to the average yield for the period 2010-2014. This was due to irregular rainfall, which disrupted the water balance during critical stages of vegetation, as well as spring frosts, which damaged seedlings and reduced plant resistance to subsequent stress conditions. In Northern Europe, the extension of the growing season contributed to a 5.5% (±1.5%) increase in barley yield in 2022 compared to the average yield for the period 2010-2014, as more favourable temperatures and a longer growing season provided favourable conditions for biomass accumulation, while precipitation levels remained sufficient to meet the needs of the crop being grown. In addition to significant quantitative changes, the quality indicators of the yields obtained also changed. The author collected data on the micronutrient content in wheat and presented it in Table 2.

Table 2. Changes in micronutrient content in wheat in EU regions (2015-2024, % compared to 2010-2014)

Region	Protein	Iron	Zinc
Southern Europe (Spain, Italy, Greece)	-7.4 (±0.9)	-9.1 (±1.1)	-6.8 (±0.8)
Central and Eastern Europe (Germany, France, Poland)	-4.8 (±0.7)	-6.2 (±0.8)	-5.1 (±0.6)
Northern Europe (Sweden, Finland, Denmark)	-2.3 (±0.5)	-3.5 (±0.6)	-2.9 (±0.5)

Source: compiled by the author based on research by I. Al-Hadeethi *et al.* (2019) and Eurostat (n.d.)

Analysis of Table 2 shows that the protein content in wheat grown in Southern Europe decreased by 7.4% (±0.9%), and iron content decreased by 9.1% (±1.1%). These changes were caused by increased CO_2 concentrations in the atmosphere and heat stress on crops. In Central Europe, the decrease was 4.8% (±0.7%) for protein and 6.2% (±0.8%) for iron, and in Northern Europe, it was 2.3% (±0.5%) for protein. The change in these indicators poses a particular threat, significantly reducing the quality characteristics of crops. This is reflected in a reduction in protein, iron and zinc content. Such changes indicate the spread of the phenomenon of "hidden hunger", which has hidden but serious long-term consequences for public health and the sustainability of global food systems. Thus, climate change in the agricultural sector goes beyond a purely agrotechnical problem and requires consideration of socio-economic and medical factors.

Assessments of the effectiveness of adaptation strategies in agriculture, such as the introduction of climate-resilient crops, the use of precision farming and remote monitoring technologies, have all yielded positive results.

Alongside technological solutions (precision farming, satellite monitoring), approaches that combine institutional adaptation and the involvement of local communities are becoming increasingly important. In Bangladesh, for example, the integration of adaptation systems into advisory services enabled more than 12,000 agricultural advisers to implement localised solutions based on community vulnerability analyses. The implementation of localised adaptation systems through advisory services in Bangladesh had a comprehensive and multi-level effect, namely: firstly, it significantly increased food security, as farmers received recommendations adapted to local conditions, which reduced crop losses during droughts, floods and other extreme weather events; secondly, it improved the economic stability of farmers, as the optimisation of resources (water, fertilisers, seeds) and the introduction of sustainable agricultural technologies reduced production costs and increased yields under stressful conditions (CARE International, 2009).

In addition, the system has helped to improve the adaptive skills of communities: farmers and local advisors have gained knowledge about climate risks and how to manage them, enabling more effective planning of agricultural work and development strategies at the local level. Thanks to the wide coverage of more than 12,000 agricultural advisors, this approach became scalable and integrated into the local advisory service system, enabling sustainable results to be achieved in many communities simultaneously. Overall, the implementation of localised adaptation systems in Bangladesh has had a systemic effect: increasing food and economic security, strengthening climate change adaptation skills, and developing the capacity of communities to respond effectively to future climate challenges (CARE International, 2009). In Mozambique, on the other hand, farmer field schools have helped to spread agroforestry strategies among the population, conserve moisture and manage crops, thereby reducing climate risks and increasing crop yields (Intergovernmental Panel on Climate Change, 2022). Table 3 provides a comparative analysis of the implementation of adaptation technologies in Mozambique and Bangladesh compared to European countries.

Table 3. Comparative analysis of the economic efficiency of adaptation strategies in Bangladesh, Mozambique and European countries

Country/region	Strategy implemented	Yield increase (%)	Cost reduction (%)	Income growth (%)
Bangladesh	Localised advisory services, sustainable varieties	10-15	5-7	8-12
Mozambique	Farmers' field schools, agroforestry	8-12	3-5	6-10
Central and Eastern Europe (Germany, France, Poland)	Precision farming technologies, automated irrigation	4.1	3-4	4-5
Northern Europe (Sweden, Finland, Denmark)	Satellite monitoring of pests and diseases	3.8	2-3	2,4
Southern Europe (Spain, Italy, Greece)	Drought-resistant wheat varieties	5.6	1-2	3-4

Source: compiled by the author based on research by F. Tubiello *et al.* (2008), CARE International (2009), P. Lamichhane *et al.* (2022), Ukraine rapid damage and needs assessment... (2023), European Environment Agency (2024)

Analysis of Table 3 showed that farmers in Bangladesh and Mozambique have limited access to finance and innovative crop production technologies. The greatest economic impact in these countries was achieved through localised advisory services, field schools and agroforestry, which helped to raise awareness of new technologies among local farmers. As a result, crop yields in these countries increased by 8-15%, and farmers' incomes grew by 6-12%, demonstrating the high importance of socio-institutional approaches. In test regions in Spain, the introduction of drought-resistant wheat varieties increased yields by 5.6% (±1.2%), which directly contributed to stabilising the domestic food balance in conditions of water scarcity and reduced the need for external grain imports. This improved the situation in terms of food security (Tubiello *et al.,* 2008; Lamichhane *et al*., 2022). The introduction of precision farming technologies in Central Europe reduced crop losses due to precipitation by 4.1% (±0.9%), which reduced fluctuations in farmers' incomes, cut the cost of agrotechnical measures, and strengthened the economic sustainability of agricultural production, which is a key factor in ensuring long-term food security. Meanwhile, in Northern Europe, the use of satellite monitoring of pest and disease spread has reduced the negative impact of fungal diseases by 3.8% (±0.7%) and reduce fungicide costs, enabling agricultural producers to increase profitability by an average of 2.4%, which contributed to the economic efficiency of the crop production sector (European Environment Agency, 2024). Although the economic effect in European countries is slightly lower in percentage terms, it is more stable and scalable thanks to technological solutions: precision farming, automated irrigation systems, and satellite monitoring. As emphasised by S.K. Balasundram *et al*. (2023), digital agriculture (precision farming) can not only increase resource efficiency, but also serve as a tool for increasing crop yields and reducing greenhouse gas emissions. A comparative analysis of the results obtained with literature sources confirmed their reliability. In particular, the results of the study are consistent with the conclusions of H. Fraga *et al*. (2012), which indicate the high vulnerability of Southern Europe to droughts. Similarly, the results regarding increased crop yields in Northern Europe coincide with the data of J.E. Olesen *et al.* (2011). The study by D.E. Medek *et al.* (2021) explains the observed decrease in the nutritional value of wheat by the phenomenon of "hidden hunger," which is confirmed by data on the decrease in protein and iron content. In addition to cereals, climate change also affects vegetable and fruit crops. In Southern Europe, tomato yields have fallen by 12% due to heat stress and water shortages, while in Central Europe, apples have suffered from late frosts, reducing yields by 7% in 2023 (Eurostat, n.d.). In Northern Europe, rising temperatures have led to an expansion of vineyards, but have also increased the risk of fungal diseases (Olesen *et al*., 2011). These changes make it more difficult to ensure a diverse diet, which is key to food security.

At the same time, the data obtained indicate an uneven distribution of access to adaptation technologies, as highlighted in the work of M. Zurek *et al*. (2022). This factor reduces the overall effectiveness of adaptation to climate change and other challenges. The practical value of the study lies in identifying the need for region-specific adaptation strategies that take into account both agroclimatic conditions and socio-economic factors. It is important to note that building adaptive capacity is impossible without strengthening horizontal communication between farmers and vertical coordination between local and national levels. As the experience of Uganda has shown, the creation of public platforms for the adaptation of the agricultural sector to the negative impact of various factors has contributed to the transfer of practices to the level of state strategy, although limited budgets and weak institutional support remained barriers. India also demonstrates the effectiveness of the transition from local experience to national policy through evidence-based approaches, including vulnerability monitoring and community participation in decision-making (Watershed Organisation Trust, 2014; Global Centre on Adaptation, 2022).

Another significant factor that has had and continues to have a major impact on global food security is the war in Ukraine. Before the full-scale war began in February 2022, Ukraine played a strategic role in the global food market. According to the Food and Agriculture Organization of the United Nations (2022), it was one of the three largest exporters of maize, ranked fourth in terms of wheat exports and first in terms of sunflower oil supplies. Every year, Ukraine exported food to more than 150 countries, accounting for up to 12% of global wheat exports. More than 40% of agricultural products were exported to European Union countries, where Ukrainian grain was used as feed and to stabilise domestic markets (Food and Agriculture Organization of the United Nations, 2022). Until 2022, Ukraine's food security was at an acceptable level: according to Economist

Impact (2022), Ukraine ranked 58th among 113 countries in 2021. Ukraine had a developed infrastructure, which contributed to the development of agricultural exports. In particular, it had Black Sea ports (Odesa, Chornomorsk, Yuzhne), over 20 million tonnes of elevator capacity, and a railway network integrated into European logistics. However, the start of a large-scale invasion (2022) caused a shock to the agri-food system of Ukraine and countries around the world that depend on raw material exports from Ukraine. According to World Bank estimates, more than 30% of Ukraine's agricultural land was either occupied or mined and became inaccessible due to hostilities (Ukraine rapid damage and needs assessment..., 2023). In 2022-2023, the most damage was done to the Kharkiv, Kherson, Zaporizhzhia, Luhansk, and Donetsk regions, which provided over 45% of global wheat and barley exports. The bombings damaged elevators, dryers, tractor stations, grain storage facilities, and logistics centres. In particular, over 15 million tonnes of grain and production capacity were lost or damaged (KSE Institute, 2023). Another critical problem was the mining of agricultural land. According to the United Nations Mine Action Service (2023), about 174,000 km² of Ukraine's territory (almost a third of the total area) needs to be demined, making large areas of agricultural land (2.5 million hectares) unusable for years to come. The real scale of the war's impact on agricultural production is reflected in official statistics. In 2022, the gross harvest of cereals and legumes in Ukraine fell from 86 million tonnes (2021) to 55.3 million tonnes (2022), i.e. by 36% (State Statistics Service of Ukraine, 2024). Crops such as winter wheat, maize and barley were particularly affected. Due to a lack of fuel and a shortage of plant protection products and agrochemicals (most of which were imported), many farms were unable to carry out spring field work in full. The decline in the cultivation of these crops led to a reduction in exports (Table 4).

Table 4. Ukraine's grain exports in 2021 and 2022

Crop	2021 (million tonnes)	2022 (million tonnes)	Change (million tonnes)	Change (%)
Maize	23	17.7	-5.3	-23
Wheat	20	11.8	-8.2	-41
Total grain exports	44.7	28.8	-15.9	-35.6

Source: compiled by the author based on data from O. Shubravska & K. Prokopenko (2022), Ukrainian Club of Agrarian Business (2024), V. Skribans *et al.* (2024)

The changes in exports shown in Table 4 have significantly affected food security in Ukraine and worldwide. The largest decline occurred in the wheat segment (-41%), while maize exports decreased by 23%. The main factors behind this negative trend were military actions that led to the blockade of Black Sea ports and the destruction of logistics infrastructure and storage facilities (Shubravska & Prokopenko, 2022). Another factor that significantly affected exports was the reduction in cultivated areas and, consequently, in harvests. Logistical barriers related to the overload of rail and road routes, increased transport costs, and dependence on ports in Romania, Poland, and the Baltic states also had a significant impact.

Thus, the key determinants of the decline in grain exports in 2022 were the combined effects of military action, production and logistical constraints, which significantly reduced the export potential of Ukraine's agricultural sector. Before the war, approximately 90% of Ukraine's agricultural exports were carried out through Black Sea seaports. However, after the war began, Russia blocked shipping from Ukrainian ports, creating the risk of famine for countries dependent on Ukrainian grain, primarily in North Africa, the Middle East and Asia. The global response to this was the Black Sea Grain Initiative, signed in July 2022 under the auspices of the UN and Turkey, which allowed the export of more than 33 million tonnes of grain during the year of the initiative's operation (United Nations, 2023). In addition, instead of maritime exports, land-based "Solidarity Lanes" were created through Poland, Romania and Slovakia (Skribans *et al.*, 2024). However, these routes have low throughput capacity, are more expensive and more difficult to coordinate. In addition, they have led to large quantities of Ukrainian grain entering the markets of neighbouring countries, causing conflicts with local farmers and political tensions within the EU (European Commission, 2023).

Ukraine's national food security has also been negatively affected. According to estimates by the Food and Agriculture Organization (2023), the proportion of the Ukrainian population without regular access to safe food increased from 6.5% in 2021 to 22.4% in 2023. The situation is worst in the frontline regions and among internally displaced persons (IDPs), who numbered more than 4.5 million in 2024. Food prices in Ukraine have risen significantly: according to the State Statistics Service of Ukraine (2024), the average annual inflation rate for food products in 2022 was 34.1%. This has had a negative impact on the availability of quality food for low-income groups. It should be noted that Ukraine's agriculture sector has been under the greatest pressure due to the war, and the industry is undergoing significant transformations. Thus, the area under grain crops has decreased by 27.6% compared to the pre-war period, while the decrease in oilseed crops was less significant – 5.6%. Vegetable growing areas have shifted to the central and western regions: the Kyiv region has increased its area by 22.5%, while Vinnytsia, Lviv and Volyn have increased theirs by 7-8%. The structure of cultivated areas has also changed: the share of grain crops decreased by 6.4 percentage points, while oilseeds increased by 4.9 percentage points, due to infrastructure losses and market fluctuations. Despite the overall reduction in cultivated areas, gross production is expected to grow in 2025, in particular due to maize cultivation and the adaptation of crop structures to new challenges. The high share of oilseeds (38% of the value of production) also indicates that they remain an export priority (Lupenko *et al*., 2025). An analysis of the impact of the war in Ukraine on food security showed that it has become another factor in the food shock. According to data from the Organisation for Economic Co-operation and Development (2023), in March – May 2022, global prices for wheat jumped by 43%, maize by 20%, and vegetable oil by more than 30%. This put extra pressure on the food systems of countries that import these products, like Egypt, Lebanon, and Pakistan.

For the European Union, the consequences were twofold: firstly, there was a need to compensate for lost imports from Ukraine through domestic production, which prompted some countries to temporarily relax environmental standards, in particular by allowing the cultivation of some protected lands; secondly, the influx of Ukrainian grain into neighbouring countries such as Poland, Slovakia and Hungary caused domestic prices to collapse and a wave of farmer protests, forcing the European Commission in 2023 to allocate compensation packages to the affected countries and temporarily restrict imports of certain goods (Organisation for Economic Co-operation and Development, 2023). The international community responded to these challenges by providing humanitarian, technical and financial support to Ukraine's agricultural sector. In particular, the FAO is implementing programmes aimed at demining agricultural land, providing farmers with seeds and microgrants, and developing logistics in the western regions of the country. As part of the agricultural land demining programme, agricultural land is being cleared of explosive objects, allowing farmers to return to safe land cultivation. In parallel with this, there is a programme to distribute certified seeds and microgrants, which helps small and medium-sized producers to restore the profitability of their farms. In addition, in response to the destruction of logistics routes in the central and southern regions, measures are being taken to develop logistics infrastructure in the western part of the country, including the modernisation of warehouses, support for transport corridors to the EU borders and strengthening the capacity of agricultural cooperatives (Food and Agriculture Organization of the United Nations, 2023). Collectively, these measures aim to reduce the vulnerability of Ukraine's food sector, ensure the continuation of the production cycle and stabilise export flows.

Despite everything, Ukraine has the potential to remain a key player in the food market. Despite all the challenges, it is worth noting the positive dynamics in 11 regions of Ukraine, which have increased their cultivated areas despite the nationwide decline in the agricultural sector – most notably in Lviv (+5.8%) and Odesa (+4.9%) regions. These regions could become catalysts for the restoration of national food potential in the post-war period (State Statistics Service of Ukraine, 2024). In addition, the war has accelerated the need to transform Europe's agri-food systems towards increasing food reserves, improving the reliability of logistics chains and diversifying imports. This creates an opportunity for Ukraine to become a long-term strategic partner with the EU in the field of food security (Shubravska & Prokopenko, 2022).

The results of the study indicate regional asymmetry in the impact of climate change on crop yields, product quality, and the effectiveness of adaptation strategies in European Union countries. A similar study was conducted by M. Trnka *et al.* (2019), which found that Southern Europe is most vulnerable to climate change due to frequent droughts and moisture deficits. This study is fully consistent with the author's research data, which shows a 15.3% (±2.1%) decrease in wheat yield in Spain. Despite this, a study conducted by J.E. Olesen *et al.* (2011) showed a positive impact of climate change on yields in Northern Europe, particularly for barley, which was also recorded in this study (+6.2% yield in Sweden and Finland). Thus, these results confirm the trends identified in the present analysis. In addition, D.E. Medek *et al.* (2021) investigated the reduction in micronutrient content in cereal crops under the influence of increased CO_2 levels and heat stress. Their conclusions are consistent with the author's findings regarding the reduction in protein, iron and zinc content in wheat, particularly in Southern Europe. Thus, the author's data and the studies cited confirm the threat of widespread hidden hunger in the world.

A study by M. Zurek *et al.* (2022) highlighted the unequal access to adaptation technologies between different regions, a fact confirmed in the author's study. In particular, Central Europe has implemented precision farming technologies that have reduced crop losses, while Southern Europe has remained more vulnerable and less effective in implementing innovative technologies. In addition, H. Fraga *et al.* (2012) pointed out in their research the critical vulnerability of the agricultural sector in Southern Europe to climate risks, which was confirmed by the author's finding of a more than 10% decrease in yields for major crops. A study by D. Deryng *et al.* (2014) found that heat waves cause a significant reduction in maize and soybean yields, which is consistent with the author's finding of an 8.7% (±1.8%) reduction in maize yields in Central Europe in 2022.

One of the important aspects of ensuring food security in conditions of war and economic instability is the adaptation of national strategies, particularly in Ukraine. As noted by I. Cherven *et al.* (2024), effective food policy must take into account not only external challenges such as war and climate risks, but also internal socio-economic factors that affect the sustainability of the agricultural sector. Research by C. Rosenzweig *et al.* (2020) indicates the need to take into account both agro-ecological and socio-economic conditions when implementing adaptation strategies. The results of the study also reveal the effectiveness of combining technological and institutional solutions, in particular the involvement of local communities. Thus, the results of the study coincide with the research of other scientists. Regarding the impact of the war, a report by the Organisation for Economic Co-operation and Development (2023) recorded an increase in world prices for wheat (by 43%), maize (by 20%) and vegetable oil (by 30%) in March – May 2022. These data fully correspond to the estimates made by the author of the article. Studies by I. Stashkevych (2025), F. Lin *et al.* (2023) and D. Saccone & E. Vallino (2025) showed how changes in grain export routes from Ukraine in 2022-2023 affect global trade in Ukrainian grain and how military actions on the territory of Ukraine have affected global food security. A study by N. Jia *et al.* (2024) analysed in detail how the war in Ukraine has affected global food production and exports, particularly of cereals and oilseeds. It was estimated that as a result of the war, wheat, barley and oat production in Ukraine fell by 20-30% in 2022. This led to a 20% increase in international grain prices during the first three months after the start of the conflict. Low- and middle-income countries were particularly affected, with food prices rising by 40-50% and more than 13 million people at risk of starvation. In addition, more than 20 countries, including India and Kazakhstan, have imposed restrictions or bans on grain exports, further exacerbating the situation on global food markets.

The results of the author's research are consistent with current scientific literature and official statistics, which increases their reliability. The similarities with the results of other authors confirm the existence of consistent trends, such as declining yields in the South, growth in the North, deteriorating grain quality, and uneven access to innovation. Thus, the results of this study not only confirm pan-European trends, but also refine them using the example of different countries in the context of the war in Ukraine and growing climate challenges.

CONCLUSIONS

The study found that climate change and the war in Ukraine have a systemic, multidimensional and long-term impact on food security. It has been proven that climate change has the strongest impact on the agricultural sector. These changes have led to a decrease in the yield of major crops in 2022 compared to the period from 2010 to 2014 (in particular, wheat in Southern Europe by 15.3% ± 2.1%, and maize in Central Europe by 8.7% ± 1.8%), a deterioration in their quality, and increased risks for socially vulnerable groups. Northern Europe, although showing productivity growth due to the lengthening of the growing season (e.g., barley yields in Sweden and Finland by +6.2%), still faces new agronomic challenges, in particular the spread of fungal diseases and phytopathogens. The study confirms the need to implement effective adaptation strategies, primarily such as: the use of climate-resistant varieties, digital technologies for "precision farming" (which reduced crop losses in Central Europe by 4.1% ± 0.9%), but there is still a need to ensure access to such solutions for all agricultural market players, including small farmers. The need for institutional support, regionalisation of policies and mechanisms for financing such adaptation measures is a critical condition for an effective response to crises and climate challenges. The study also found that the war in Ukraine has had a significant impact on global and European food chains, significantly destabilising markets and causing a sharp rise in world prices for wheat (+43%), maize (+20%) and vegetable oil (+30%) in March-May 2022. Nevertheless, Ukraine still has the potential to remain a key strategic partner of the EU in the field of food security. Of course, restoring pre-war levels of crop production requires the use of all available resources, in particular the demining of land (2.5 million hectares) that has been taken out of agricultural production. Despite all the challenges, positive dynamics were observed in 11 regions that have increased their sown areas despite the nationwide decline, with the largest increases in Lviv (+5.8%) and Odesa (+4.9%) regions. These regions could become catalysts for the restoration of national food potential in the post-war period. Ensuring food security in the context of climate change and the war in Ukraine requires not only technological solutions, but also profound institutional restructuring, the integration of adaptation policies and the strengthening of cross-border cooperation. Further research should focus on developing interdisciplinary models that take into account biophysical, economic and social aspects in order to formulate effective food security strategies for the 21st century.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

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Вплив кліматичних змін у світі та російської агресії в Україні на глобальну продовольчу безпеку

Анотація. Проблема продовольчої безпеки набула особливої актуальності в умовах посилення кліматичних змін та геополітичних загроз, зокрема війни в Україні. Метою дослідження було визначення впливу кліматичних змін та впливу російської агресії в Україні на функціонування глобальних агропродовольчих систем. Основна увага була приділена аналізу впливу екстремальних погодних явищ, дефіциту води, зміни режиму опадів та військових дій на врожайність, харчову якість та цінність сільськогосподарських культур та функціонування ланцюгів постачання. Методологічною основою дослідження було поєднання кількісного аналізу статистичних даних з якісним аналізом регіональних адаптаційних стратегій та соціально-економічних наслідків. Результати свідчать про високу вразливість Південної та Центральної Європи. Зафіксовано зниження врожайності пшениці, кукурудзи та ячменю в Південній і Центральній Європі, тоді як у Північній Європі спостерігалося її зростання внаслідок подовження вегетаційного періоду. Також, виявлено погіршення харчової цінності продукції через зменшення вмісту мікронутрієнтів. Аналіз підтвердив ефективність впровадження кліматостійких технологій, точного землеробства та участі громад в адаптаційних процесах. Окрему увагу приділено впливу повномасштабної війни в Україні на продовольчу безпеку. Вона спричинила скорочення посівних площ, втрати виробничих потужностей, порушення логістики та експорту сільськогосподарської продукції, різке зростання цін на продукти харчування та викликала соціальну напругу в країнах-імпортерах. Узагальнення результатів підкреслює потребу в інтегрованому та регіоналізованому підходах до політики продовольчої безпеки в умовах підвищених кліматичних шоків та інших ризиків. При цьому, впровадження кліматостійких технологій, диверсифікація постачання та посилення міжнародної кооперації є критично важливими для формування стійких агропродовольчих систем майбутнього. Практичне значення дослідження полягало у формуванні науково обґрунтованих підходів адаптації сільськогосподарського сектору до кліматичних змін та впливу війн

Ключові слова: сільське господарство; адаптаційні стратегії; стійкість аграрного сектору; повоєнне відновлення; прихований голод