frontiers | Frontiers in Sustainable Food Systems

TYPE Conceptual Analysis
PUBLISHED 24 November 2025
DOI 10.3389/fsufs.2025.1657103

Check for updates

OPEN ACCESS

EDITED BY
Albie F. Miles,
University of Hawaii–West Oahu,
United States

REVIEWED BY
Shonil Anil Bhagwat,
The Open University, United Kingdom
Margherita Squarcina,
University of Göttingen, Germany

*CORRESPONDENCE
Sydney Waloven
✉ walovens@msu.edu
Jianguo Liu
✉ liuji@msu.edu

RECEIVED 30 June 2025
ACCEPTED 28 October 2025
PUBLISHED 24 November 2025

CITATION
Waloven S, Manning N, Remer M, Yu X, Huang J, Jia N and Liu J (2025) A metacoupled approach to analyzing multiple shocks affecting multiple systems. *Front. Sustain. Food Syst.* 9:1657103. doi: 10.3389/fsufs.2025.1657103

A metacoupled approach to analyzing multiple shocks affecting multiple systems

Sydney Waloven*, Nicholas Manning, Michele Remer, Xiang Yu, Jincheng Huang, Nan Jia and Jianguo Liu*

Center for Systems Integration and Sustainability, Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI, United States

Shocks have significant impacts on many aspects of coupled human and natural systems (e.g., countries), leading to various social, environmental, and economic effects. While numerous scholars have studied impacts of shocks on one system, little research has explicitly addressed the cascading effects of multiple shocks on multiple systems. Due to the interacting nature of multiple systems in the globalizing world, there may be complex cascading consequences across multiple systems. Integrated frameworks are needed to help untangle the complexity. The metacoupling framework is one such integrated framework that conceptualizes human-nature interactions within and across nearby and distant systems and has the unique applicability to analyze how multiple shocks spread and interact across systems. To demonstrate the application of the framework, we evaluated the cascading impacts of two global shocks (the COVID-19 pandemic and Russia-Ukraine war) on the agri-food supply chains in Ukraine and beyond. We defined four shock and system combinations according to the number of shocks and number of systems (i.e., one shock-one system, multiple shocks-one system, one shock-multiple systems, multiple shocks-multiple systems). By using the metacoupling framework, we identified distinctive characteristics and similarities among different combinations of shocks and systems. In each multiple shock combination, the shocks exposed vulnerabilities in agri-food sectors such as trade inefficiencies and overreliance that exacerbated economic, environmental, and social issues (e.g., food insecurity, supply chain disruptions, and surges in food prices). Only evaluating one-shock combinations oversimplify the complex and compounding nature of multiple-shock events, where impacts directly attributed to a later shock may be lingering consequences of a previous shock. Failing to consider multiple shocks across multiple systems may lead to incomplete information and misleading conclusions that directly hinder the improvement of system resilience to future shocks. This study demonstrates the metacoupling framework's ability to conceptualize the complexity of multiple shocks and recognize their often overlooked impacts in single-shock or single-system analyses. Understanding the interdependence of systems and cross-boundary multiple shocks can promote multisectoral collaboration between countries to enact resilient and transformative agri-food sector change and mitigate the repercussions on United Nations Sustainable Development Goals.

KEYWORDS

metacoupling framework, multiple shocks, resilience and vulnerability, Russia-Ukraine conflict, COVID-19, agri-food systems

Introduction

Shocks are sudden disturbances that result in a substantial change in the functioning of a system (e.g., country) and deviate from the system's long-term patterns or trends (Bănică et al., 2020; Banks et al., 2013; Walker et al., 2012) (Table 1). Shocks such as war, economic collapse, disease, and natural disasters have far-reaching and heavily impactful consequences on different dimensions (e.g., environmental, economic, social). Many studies examining the drivers, mechanisms, and effects of these global shocks have concentrated on various elements of human and/or environmental interactions. To understand how shocks reshape these interactions across multiple scales, it is necessary to define a 'system' in this context.

A system refers to an interconnected set of human and natural components that maintain certain functions or patterns over time, i.e., a coupled human and natural system (CHANS), such as a country, state, or region (Liu et al., 2007). These human and natural components encompass social, economic, and environmental subsystems such as cultural norms, demographics, governance, biodiversity, climate, and more (Liu et al., 2013). Most of the previous studies on shocks focused on one shock in one system. For example, there have been investigations into the effects of the 2008 Wenchuan Earthquake on forests in Wenchuan County (Sichuan Province, China) (Viña et al., 2011) as well as human well-being and ecosystem services in Wolong Nature Reserve of southwestern China (Yang et al., 2015). Some studies have considered the impact of a single shock on multiple systems, such as the impact of the COVID-19 pandemic on multiple land systems (Piquer-Rodríguez et al., 2023). Researchers have recently studied the impacts of the Russia-Ukraine war on global cropland expansion, biodiversity, and trade network (Jiang et al., 2023; Chai et al., 2024; Jia et al., 2024; Liu et al., 2022).

A few scholars have also begun to investigate the impact of multiple shocks on one system (da Silva et al., 2025; Machlis et al., 2022). For example, da Silva et al. (2025) studied the compound effects of drought and COVID-19 on soybean production in Brazil. Machlis et al. (2022) developed a framework for research on recurrent acute disasters. Other scholars have called for a deeper understanding of the combined impacts of severe weather events and pandemics as "colliding disasters" (Drake et al., 2023).

TABLE 1 Glossary box.

Term	Definition
Disturbance	A relatively discrete event or force that affects the characteristics of an ecosystem, community, or population and whose recovery is dependent on the event's intensity, frequency, spatial pattern, and spatial extent of the event (Tierney, 2019)
Shock	A sudden disturbance that results in a substantial change in the functioning of a system (e.g., environmental, economic, social, physical) and deviates from their long-term patterns or trends (Bănică et al., 2020; Banks et al., 2013; Walker et al., 2012)
Multiple shocks	Two or more sudden overlapping disturbances that alter the functioning of a system, compounding each disturbance's impacts
Resilience	The ability of a system to maintain or return to its current state when undergoing change such as a shock or disturbance (National Academies of Sciences, Engineering, and Medicine, 2025)
Vulnerability	The susceptibility of a system to shocks and adversity (Tierney, 2019; Pescaroli and Alexander, 2015)

However, there is a lack of studies about the impacts of multiple shocks on multiple systems, although multiple shocks may interact with each other and the world is interconnected. For instance, it is not clear how multiple shocks in one system affect multiple systems. Analyzing these wide-ranging and interconnected events requires comprehensive, interdisciplinary perspectives. The use of an integrated framework, such as the metacoupling framework (MCF) (Liu, 2023), is required to effectively conceptualize the impacts of multiple shocks on multiple systems. The MCF enables examination of how shocks operate at the local, regional, and global scales, fostering interdisciplinary analysis that can inform proactive policies, promote multi-sectoral collaboration, and drive the transformative change required to build resilient agri-food sectors and fulfill SDG 2 (Zero Hunger) and SDG 11 (Sustainable Cities and Communities, particularly, 11.5 Disaster Risk Reduction). Therefore, this paper aims to answer two major questions: "How can the metacoupling framework be applied to examine multiple shocks and systems?" and "What insights does this application reveal about cross-system and cross-scale interactions, resilience, and vulnerability?"

We address these fundamental questions by first briefly introducing the MCF. We then illustrate the application of the MCF using an example that features four shock-system combinations (i.e., one shock-one CHANS, hereafter system, one shock-multiple systems, multiple shocks-one system, multiple shocks-multiple systems). This paper uses Ukraine as a case study to apply these shock-system combinations and demonstrate the suitability of the MCF when examining multiple shocks due to the multiple compounding events (shocks) that Ukraine has undergone in the past 5 years. We highlight the differences and similarities among the four shock-system combinations using the Russia-Ukraine war, the COVID-19 pandemic, and related changes in agri-food couplings that exist at the local (intracoupled), adjacent (pericoupled), and distant (telecoupled) scales with Ukraine as the focal system. Lastly, we discuss challenges and opportunities to adapt the framework in the context of other shocks and systems. This study, within the broader research on shocks, can help inform management plans by enhancing knowledge of system resilience and interactions, while reducing vulnerability to future shocks.

Overview of the metacoupling framework in the context of shocks

The metacoupling framework (MCF) offers a useful tool to conceptualize interconnections and impacts of multiple shocks across multiple systems at various scales (Liu, 2023). Broadly, the MCF has been successfully used to examine many interdisciplinary issues, such as fisheries and watershed management (Carlson et al., 2020a; Merz et al., 2020), food security related to food-energy-water nexus (Xu et al., 2020), international crop trade (da Silva et al., 2021), impacts of sand mining on global marine biodiversity (Torres et al., 2025), analysis of nature's contributions to people (Mayer et al., 2025), and increasing globalization of Arctic systems (Kapsar et al., 2022).

The MCF can group the complex socioeconomic-environmental interactions of shocks into three major types of couplings based on the proximity of the interaction (in space or time). There are three types of couplings in the overall MCF: intracoupling (within a system), pericoupling (between adjacent systems), and telecoupling (distant systems) (Liu, 2017). An intracoupling is a process or interaction that occurs within a focal system, while a pericoupling focuses on interactions between neighboring systems, such as the focal system and its adjacent counterpart. Lastly, a telecoupling connects distant systems. Two or more systems are coupled through *flows*. *Agents* foster the transmission of these flows. *Causes* produce couplings between systems, resulting in socioeconomic and environmental *effects* (Liu et al., 2013). For example, a critical peri-and telecoupling connecting coupled human and natural systems [CHANS (Liu et al., 2007)] is trade since it connects multiple adjacent and distant countries through the flow of goods, materials, and money.

The telecoupling framework (TCF) within the MCF is notably the most widely applied and has been used in a wide range of studies related to shocks, such as the red imported fire ant invasion (Liu et al., 2013), shocks affecting non-renewable mineral resources such as those essential for agricultural fertilization (Barbieri et al., 2022), and earthquake impacts on the Wolong Nature Reserve for panda conservation in China (Yang et al., 2015; Viña et al., 2007; Liu and Viña, 2014; Yang et al., 2016; Zhang et al., 2018). However, research evaluating multiple shocks and comprehensive *metacoupling* interactions, such as pericoupling and intracoupling, is lacking.

Recent events, such as the Russia-Ukraine war and the COVID-19 pandemic, have demonstrated the consequences of multiple shocks and the need for the use of the MCF in research on their effects. For example, the Russia-Ukraine war has caused the mass displacement of people from their homes in Ukraine and has negatively impacted food and water security both locally and distantly through global trade. These impacts of the war in Ukraine have exacerbated the nation's human health and livelihoods already grappling with the ramifications of the COVID-19 pandemic (Nchasi et al., 2022).

The MCF can help identify vulnerable regions that are at greater risk for compounding impacts (e.g., food insecurity) of multiple shocks. If a country is experiencing severe effects of shocks without proper time to recover, then it is likely to be disproportionately impacted by another shock as opposed to a country whose resilience has not already been strained (Dominey-Howes, 2018). Vulnerabilities of systems can perpetuate the effects of shocks across time and space. Demographic differences such as class, ethnicity, gender, and race, in addition to disparities in income, integrity of community infrastructure and institutions, and strength of government recovery plans, play a significant role in a country or region's capacity to rebound after a shock (Tierney, 2019). Therefore, understanding differences and similarities in areas experiencing similar shocks can generate insights into mitigation mechanisms and create appropriate management plans that consider these factors to mitigate vulnerability.

In the next section, we explore four conceptual combinations that consider four different pairings of the number of shocks and number of systems they affect, i.e., single versus multiple shocks and single versus multiple systems (Figure 1). These four combinations are used to group effects and interactions for comparison. The ultimate goal is to understand multiple shocks across multiple systems using Ukraine as a case study. Focusing on Ukraine as a focal system provides an optimal opportunity to examine the interconnections and couplings at the local, adjacent, and distant scales, while using an organized method such as the MCF to characterize these interactions. The four shock-system combinations are used together with the MCF to depict the specific interactions that are revealed when more coupled systems are considered (one system - > intracoupled, multiple systems - > pericoupled/telecoupled) and the components that may get overlooked at only the local scale.

Agri-food supply chains in Ukraine and beyond across a metacoupled world

We use Ukraine's agri-food sector and beyond as a demonstration of the four shock-system combinations (Figure 1). Our focal country of interest is Ukraine. Ukraine is one of the world's major breadbaskets due to being a leading producer and exporter of barley, corn, sunflower-seed oil, and wheat (Leal Filho et al., 2023). Impairments to the supply of these essential commodities from a major exporter have drastic consequences for both nearby and distant importing countries. Therefore, Ukraine's role as a major food producer and exporter makes it an excellent focal system to discuss how shocks affect its adjacent and distant systems using the MCF. Table 2 demonstrates some elements of the Russia-Ukraine war and pandemic in the context of the metacoupling framework.

Table 2 also demonstrates similarities among the components of the MCF such as how the war and pandemic have both resulted in the decreased availability of food stuffs (Behnassi and El Haiba, 2022), disruptions in the food supply chain (Lin et al., 2023), and subsequent food insecurity both within Ukraine and countries that rely on Ukraine for exports (Behnassi and El Haiba, 2022; Liu et al., 2023). Ukrainian citizens experience several consequences economically (e.g., food price surges) (Pereira et al., 2022), environmentally (e.g., water contamination, harmful algal blooms) (Vyshnevskyi et al., 2023; Shumilova et al., 2023; Hryhorczuk et al., 2024), and biologically (e.g., spread of disease) (Lin et al., 2023; Hryhorczuk et al., 2024). A summary of the environmental, social, and economic impacts felt by the focal system and adjacent and distant systems is in Table 3. Ukrainians face disproportionate impacts of the war compared to their neighbors and people in distant places, due to their proximity and the added strain on the country's preexisting vulnerabilities from the pandemic (Lin et al., 2023; Liu et al., 2023). Citizens in distant countries experience changes in trade routes, trade agreements, and sales prospects due to blocked ports and routes typically used (Leal Filho et al., 2023; Bizzarri, 2022). However, citizens of these distant and adjacent countries still encounter impacted food security and surges in food prices (Leal Filho et al., 2023; Behnassi and El Haiba, 2022; Liu et al., 2023).

Ukraine has undergone massive physical, socioeconomic, political, and livelihood consequences due to Russia's invasion in 2022. Before the war, Ukraine accounted for 46, 9, 17, and 12% of exports for sunflower-seed oil, wheat, barley, and corn, respectively (Leal Filho et al., 2023). As can be seen from Figure 2, Ukraine's total food production of its five major crops fell sharply after Russia's invasion in 2022. The production of sunflower-seed oil, barley, and wheat has declined significantly from 2021 to 2022, by 0.85 million tons, 3.20 million tons, and 8.17 million tons, respectively (UN Comtrade, n.d.). These agricultural products are key contributors to Ukraine's total

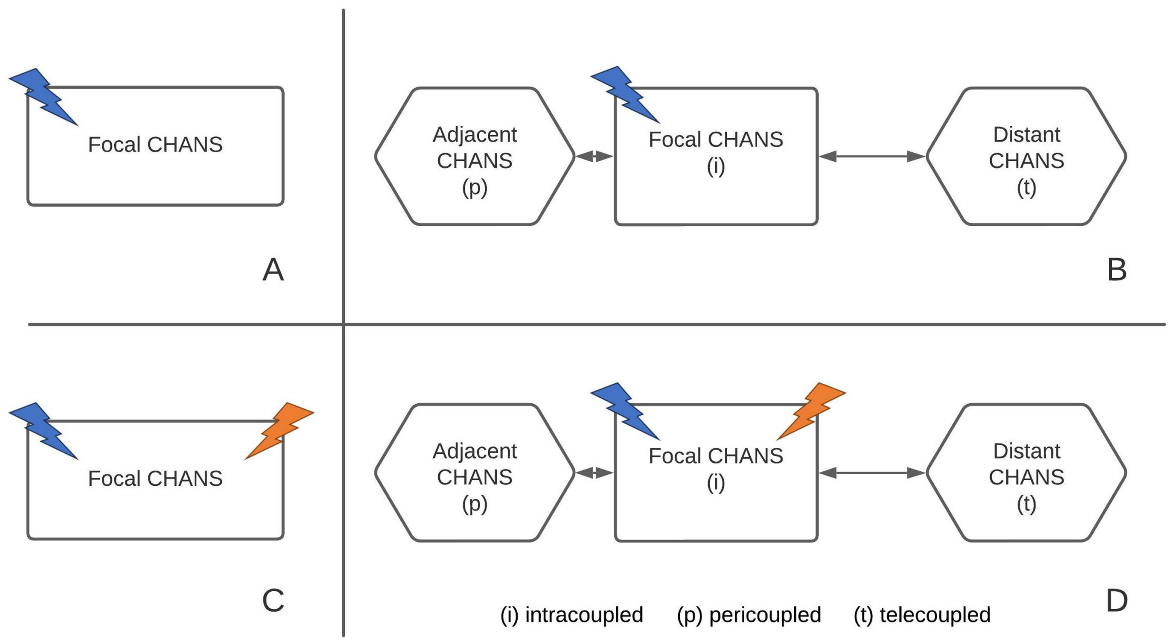

FIGURE 1
Four combinations of shocks affecting coupled human and natural systems (CHANS). **(A)** One shock, one system (one shock impacting one system); **(B)** One shock, multiple systems [one shock impacting the focal and adjacent (pericoupled) and distant systems (telecoupled)]; **(C)** Multiple shocks, one system (multiple shocks impacting one system); **(D)** Multiple shocks, multiple systems (multiple shocks impacting the focal and adjacent and distant systems). The blue- and orange-colored bolts represent two different potential shocks.

agricultural exports and play important roles in maintaining the stability of global food markets (Leal Filho et al., 2023). The next section explores how Ukraine's agri-food sector is interconnected across different scales as it experiences these shocks, using the MCF.

Shock-system interaction analysis

Here, we apply the MCF to examine the impacts of single and multiple shocks on Ukraine's agri-food sector and its coupled systems. The MCF captures specific interactions relating to food availability and access as well as system vulnerability to shocks at different scales, which is critical to the ongoing efforts to achieve several interrelated SDGs (Pereira et al., 2022).

Methods

We conceptually examine the dynamics across Ukraine's interconnected systems using the MCF to illustrate the linkages within, between adjacent, and distant systems. We synthesize existing knowledge to clarify how shocks, such as conflict and disease spread, are propagated through coupled human and natural systems. We construct a set of four combinations of shocks and systems to identify and characterize the interactions that emerge at each spatial scale while using the MCF. The one shock-one system combination describes the couplings within Ukraine related to its agri-food sector and specifically influenced by the Russia-Ukraine war. The multiple shocks-one system combination expands the systems of interest to include the nearby and distant systems connected to Ukraine's agri-food sector. The multiple shocks-one system combination broadens to include the interactions of the COVID-19 pandemic as well as the war on Ukraine. Lastly, the multiple shocks-multiple systems combination encompasses interactions both within Ukraine and across nearby and distant systems affected by the war and pandemic. As each combination expands to consider more systems of interest, this reveals the relational complexity of multiple shocks and the characteristics revealed at different scales of analysis.

Approaches using the MCF are categorized as empirical (quantitative analysis) or synthetic (integrating prior research that had not previously applied the MCF) (Carlson et al., 2020b). We utilize a synthetic approach by reviewing the current literature and identifying articles that fit the dimensions (number of relevant systems or shocks) for each combination. We conducted a literature search using Google Scholar and Web of Science Core Collection to identify scientific articles, book chapters, and government reports related to our systems and shocks of interest. Reputable news sources that provided timely or contextual information were also included when appropriate. Only texts written in English were included and publications were limited to peer-reviewed journals, chapters from edited volumes, and official websites of governments, institutions, or organizations involved in the ongoing management of the war, global food security, and the pandemic. Sources were selected based on their relevance to each scale of analysis and their contribution to understanding interactions across metacoupled scales. The search was limited to the timeframe 2000 to 2025 to encompass foundational CHANS and shock literature. The included sources were organized into the relevant combination(s) according to the components and relationships defined by the MCF to identify key interactions, patterns, flows, and effects.

Applications of the MCF can improve upon previous studies that did not consider the MCF or only applied subsets of the framework,

TABLE 2 A table highlighting various Russia-Ukraine war and COVID-19 impacts in Ukraine, in adjacent countries, and in distant countries.

Shock	System	Causes	Effects	Flows	Agents
Russia-Ukraine war	Ukraine	Destruction of the Kakhovka dam and hydropower plant (Vyshnevskyi et al., 2023; Gleick et al., 2023)	Local and downstream flooding (Shumilova et al., 2023; Gleick et al., 2023)	Water (Pereira et al., 2022; Shumilova et al., 2023)	Agricultural producers, Ukrainian citizens (Pereira et al., 2022; Shumilova et al., 2023)
			Death of many humans and other biodiversity (e.g., fish, crops) (Vyshnevskyi et al., 2023)	Water, dam debris (Pereira et al., 2022; Shumilova et al., 2023)	Water infrastructure workers (Pereira et al., 2022; Shumilova et al., 2023)
			Power loss (Pereira et al., 2022; Shumilova et al., 2023)	Electricity, information (Pereira et al., 2022; Shumilova et al., 2023)	Ukrainian citizens (Pereira et al., 2022; Shumilova et al., 2023)
			Bacterial and chemical contamination of nearby and downstream water sources (i.e., Black Sea) (Pereira et al., 2022; Shumilova et al., 2023; Hryhorczuk et al., 2024)	Pollutants (Pereira et al., 2022; Shumilova et al., 2023; Hryhorczuk et al., 2024)	Aquatic ecological communities, consumers (Pereira et al., 2022; Vyshnevskyi et al., 2023; Shumilova et al., 2023)
		Destruction of cities, homes, and healthcare infrastructure (Gleick et al., 2023)	Deterioration of public health and livelihoods (Shumilova et al., 2023), unsanitary living conditions (Gleick et al., 2023)	People, disease (Shumilova et al., 2023; Gleick et al., 2023)	Ukrainian citizens (Shumilova et al., 2023; Gleick et al., 2023)
	Adjacent Countries	Black Sea blockade (Leal Filho et al., 2023; Bizzarri, 2022)	Redirection of regional grain trade routes and spillover of exports to other countries (Leal Filho et al., 2023; Bizzarri, 2022)	Grain (Leal Filho et al., 2023; Bizzarri, 2022)	Ukrainian grain producers, transport companies, grain purchasers in adjacent countries (Leal Filho et al., 2023; Bizzarri, 2022)
		Destruction of cities, homes, and healthcare infrastructure due to the war (Gleick et al., 2023)	Citizens flee to other countries (e.g., Germany, Poland, Czech Republic) (Lin et al., 2023)	People (Shumilova et al., 2023; Gleick et al., 2023)	Embassies, citizens (Lin et al., 2023; Gleick et al., 2023)
	Distant Countries	Trade agreement and sales prospects (Leal Filho et al., 2023; Bizzarri, 2022)	Redirection of trade routes to distant countries (Leal Filho et al., 2023; Bizzarri, 2022)	Grain (Leal Filho et al., 2023; Bizzarri, 2022)	Government agencies, ship operators (Liu et al., 2022; Liu et al., 2023)
		Decreased availability of foodstuffs (Leal Filho et al., 2023; Lin et al., 2023; Bizzarri, 2022)	Trade agreements and changes in sales prospects (Leal Filho et al., 2023; Behnassi and El Haiba, 2022; Bizzarri, 2022)	Fertilizers, information (Liu et al., 2022)	Food manufacturers, fertilizer producers, citizens and consumers (Leal Filho et al., 2023; Lin et al., 2023; Bizzarri, 2022)
			Immigration of Ukrainian citizens to other countries (Behnassi and El Haiba, 2022; Lin et al., 2023)	Ukrainian citizens (Leal Filho et al., 2023; Lin et al., 2023; Bizzarri, 2022)	
			Food insecurity (Leal Filho et al., 2023; Lin et al., 2023; Bizzarri, 2022)	Citizens of countries that rely on Ukraine for exports (Leal Filho et al., 2023; Lin et al., 2023; Bizzarri, 2022)	

(Continued)

TABLE 2 (Continued)

Shock	System	Causes	Effects	Flows	Agents
COVID-19	Ukraine	Lockdowns and quarantine measures (Choudhary et al., 2022)	Decreased public health and livelihoods (Choudhary et al., 2022)	Disease, people, food, goods, money (Choudhary et al., 2022; Allam et al., 2022)	Citizens, consumers, farmers, food corporations (Choudhary et al., 2022; Allam et al., 2022)
		Overburdened healthcare systems (Choudhary et al., 2022)	Weak preventative and long-term care, insufficient medical testing/technology and staff (Choudhary et al., 2022)		
		Disruptions in the local food supply chain (Choudhary et al., 2022; Allam et al., 2022)	Food shortages and insecurity, increased costs of food and fuel (Allam et al., 2022; Liobikienė et al., 2023)		
	Adjacent Countries	Diminished trade and food supply to adjacent countries (Hryhorczuk et al., 2024)	Decline in GDPs, unsustainable production practices to compensate for losses and low supply (Hryhoruk et al., 2021)	Food, goods, money (Hryhoruk et al., 2021)	Citizens, consumers, farmers, food and trade companies (Hryhoruk et al., 2021)
		Lockdowns and quarantine measures (Choudhary et al., 2022)	Higher unemployment rate due to migrant workers forced to stay in Ukraine (Hryhoruk et al., 2021)		
	Distant Countries	Diminished trade and food supply to distant countries (Hryhorczuk et al., 2024)	Decline in GDPs, unsustainable production practices to compensate for losses and low supply (Hryhoruk et al., 2021)	Food, goods, money (Hryhorczuk et al., 2024; Hryhoruk et al., 2021)	Citizens, consumers, farmers, food and trade companies (Hryhorczuk et al., 2024; Hryhoruk et al., 2021)

such as telecoupling. For example, Chai et al. (2024) measured the telecoupled impacts in different scenarios of the Russia-Ukraine war and revealed new findings such as how global cropland in distant countries could expand and influence the severity of biodiversity loss. Applying the MCF can extend this analysis by bridging the local to global scales through integrating regional linkages at the pericoupled scale and by incorporating feedbacks that connect local and distant systems. Therefore, our conceptualization here with the MCF can support future quantitative assessments and deeper quantitative analyses that measure the specific empirical impacts of each shock on the respective flows and components.

One shock, one system

Our approach to outlining the one shock and one system example mirrors the intracoupling framework. In this case, the single shock is the Russia-Ukraine war, and the focal system is Ukraine. Therefore, the intracoupled interactions in this combination are those occurring *within* Ukraine's boundaries (i.e., system boundaries). We set our temporal scale by classifying the start of the shock as Russia's invasion of Ukraine in 2022. The war is still ongoing so there is no definitive end to the shock.

The primary intracouplings of interest are within Ukraine's agri-food sector, which has rapidly grown over the past several decades (Kholoshyn et al., 2021). The share of agricultural products as part of Ukraine's total exports made up less than 15% in 2010 and grew to more than a third in 2019 (Kholoshyn et al., 2021). By January 2020, 50% of Ukraine's total exports were agricultural products (Kholoshyn et al., 2021). The growth of Ukraine's agricultural industry is reflected by the escalating demand from foreign consumers, the rapid rise in agricultural yields and production, and the expansion of new markets (Kholoshyn et al., 2021). As summarized in Table 2, the war has multiple economic, environmental, and social causes and effects at the intracoupled scale on Ukraine's agri-food production and trade, with multiple implications for several SDGs. For example, the war has caused damage to agricultural machinery, storage areas, and resulted in the loss of livestock (Hryhorczuk et al., 2024). As of February 2023, the war had cost the sector over $6.6 billion (USD) in total value of damages and approximately $34.25 billion (USD) in agriculture-based revenue losses (Welsh, 2023). There have also been other types of infrastructure, such as water systems, damaged in the war that are likely to impact Ukraine's ability to produce food in the future, directly corresponding to impacts on SDG 2 (Zero Hunger) and SDG 6 (Clean Water and Sanitation) (Pereira et al., 2022).

A significant intracoupled effect of the war was severe damage to the Kakhovka dam and power plant due to an explosion in 2023, which resulted in several parts of the dam being destroyed (Gleick et al., 2023). Following World War II, the Geneva Convention prohibited the weaponization of water systems against civilians (Gleick et al., 2023). Despite these bans, there have still been several recorded instances of water-related incidents worldwide (Gleick et al., 2023). The Kakhovka dam was the largest hydrotechnical facility ever destroyed by war (Vyshnevskyi et al., 2023).

Downstream of the dam, numerous hectares of farmland were ruined, whereas upstream of the reservoir, as many as 580,000 hectares faced water shortages in the following year (Gleick et al., 2023), further threatening food availability and progress toward SDG 2 and

TABLE 3 Summary of environmental, social, and economic effects under four shock-system combinations (UKR, Ukraine; P, Pericoupled Systems; T, Telecoupled Systems).

Type of Effect	One shock, one system (War, UKR)	One shock, multiple systems (War, UKR + P + T)	Multiple shocks, one system (War + COVID, UKR)	Multiple shocks, multiple systems (War + COVID, UKR + P + T)
Environmental	• Farmland and soil degradation (Hryhorczuk et al., 2024) • Reduced dam inflow (Gleick et al., 2023) • Contamination of water and food with heavy metals (Pereira et al., 2022; Shumilova et al., 2023) • Heightened radiation and risk of leaks (Pereira et al., 2022; Hryhorczuk et al., 2024) • Wildfires (Hryhorczuk et al., 2024) • Military investments result in direct/indirect effects on climate change (e.g., shipping routes, military installations, pressure on natural resources) (Hryhorczuk et al., 2024)	• Increased air pollution and greenhouse gas emissions (Hryhorczuk et al., 2024) • Deforestation and habitat destruction (Hryhorczuk et al., 2024) • Burned products (e.g., military hardware/vehicles) contaminate water sources (Hryhorczuk et al., 2024)	• Increased greenhouse gas emissions (Hryhorczuk et al., 2024) • Unsustainable energy production, veering farther away from carbon-neutral agriculture (Hryhorczuk et al., 2024)	• Deforestation and urban expansion pressures on food systems (Martinho, 2022) • Land-use change and deforestation result in habitat loss for hosts of pathogens, increasing risk of transmission to humans (Martinho, 2022) • Unsustainable practices to compensate for scarce fuels and related products (Hryhorczuk et al., 2024; Allam et al., 2022)
Social	• Food insecurity (van Meijl et al., 2024) • Food security initiatives (e.g., World Food Program) (Leal Filho et al., 2023) • Decreased social cohesion, landscape aesthetics, cultural heritage, and livelihoods (Leal Filho et al., 2023) • Unsanitary living conditions (Leal Filho et al., 2023)	• Redirection of trade routes (e.g., Black Sea Grain Initiative) (Bizzarri, 2022) • Destruction of health infrastructure and strain on healthcare systems (Choudhary et al., 2022) • Decreased public health and livelihoods (Choudhary et al., 2022) • Refugee displacement (Hryhorczuk et al., 2024) • Policy shifts in renewable and nuclear energy (Hryhorczuk et al., 2024)	• Restrictive measures and lockdowns (Choudhary et al., 2022) • Overburdened healthcare systems (Choudhary et al., 2022) • Insufficient personal protective equipment, medical professionals, and related testing and technology (Choudhary et al., 2022) • Decreased public health and livelihoods (Choudhary et al., 2022) • Food insecurity (Hryhorczuk et al., 2024)	• Changes in global energy consumption patterns (Liobikienė et al., 2023) • Concerns over COVID-19 and the war contribute to short-term energy-saving behavior changes (Allam et al., 2022; Liobikienė et al., 2023) • Quarantine measures in adjacent countries lead to higher unemployment rate in Ukraine (Hryhoruk et al., 2021) • Food and energy insecurity (Allam et al., 2022; Liobikienė et al., 2023)
Economic	• Costly damage of agricultural machinery, storage, infrastructure, and lost livestock (Hryhorczuk et al., 2024) • Increased costs of food and supplies (Hryhorczuk et al., 2024)	• Exacerbation of inefficient trade logistics (International Trade Administration, 2023) • Grain export capacity greatly reduced due to unsafe passage through Black Sea but resurges after establishment of route alternatives (Leal Filho et al., 2023; Bizzarri, 2022)	• Weakened large and medium-sized enterprises (Hryhoruk et al., 2021) • Ceased operation of small enterprises (Hryhoruk et al., 2021) • Hindered socio-economic development (e.g., industry, agriculture, construction, and capital investment) for most of Ukraine's regions (Hryhoruk et al., 2021) • Restricted inflow of foreign direct investment profits (Hryhoruk et al., 2021)	• Disrupted supply chains (Hryhorczuk et al., 2024) • Increased costs of food and fuel (Hryhorczuk et al., 2024) • Decline in GDPs (Allam et al., 2022) • Inflation (Allam et al., 2022) • Decreased progress toward Sustainable Development Goals and Nationally Determined Contributions under the Paris Agreement (Allam et al., 2022)

6. Ecological shifts due to the destroyed dam have led to the emergence of several new plant habitats over the barren lake bed (The Economist, n.d.).

In addition, connected water systems in Ukraine have been polluted due to heavy metals from ammunition leaching into the water, affecting the water quality and degradation of soil and resulting

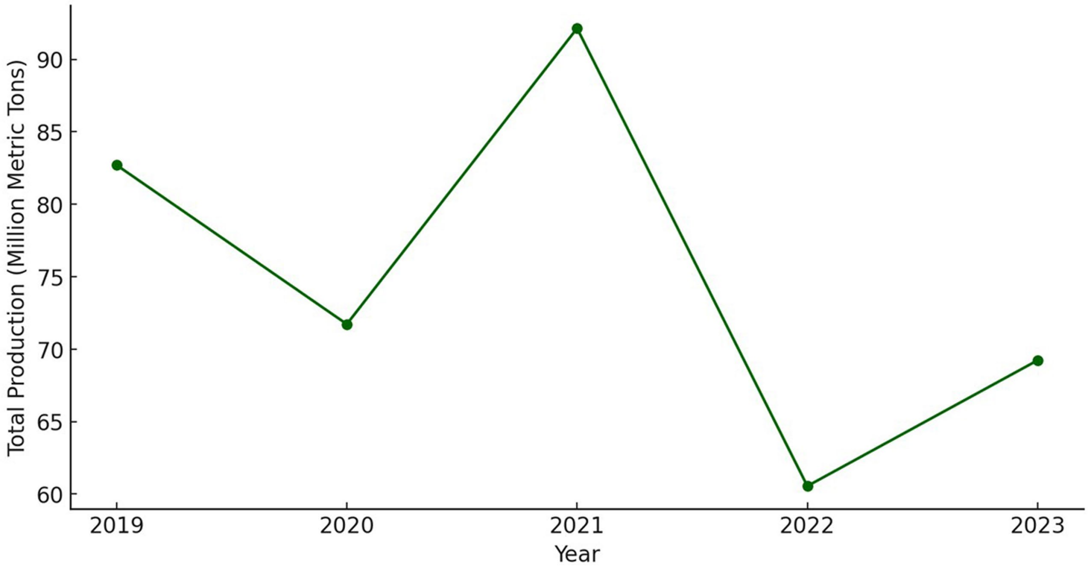

FIGURE 2
Production of five major crops (barley, maize, soya beans, crude sunflower-seed oil, and wheat) in Ukraine from 2019 to 2023 (Bănică et al., 2020).

food safety produced from those irrigated fields (Pereira et al., 2022; Shumilova et al., 2023). This series of impacts on water mirrors the impacts of climate change, which similarly have led to increasing desertification and a decline in water accessibility worldwide, representing broader challenges in realizing SDG 2 as well as SDG 6 (Dvigun et al., 2022).

Reduced water accessibility in this region is also accompanied by compromised food security that has led to the World Food Programme launching an operation to provide food to Ukrainian refugees (Leal Filho et al., 2023). These compromises to citizens' access and availability to food, combined with a loss of ecosystem services, landscape aesthetics, social cohesion, and cultural heritage, have reduced the adaptive capacity of local communities (Pereira et al., 2022). This shift in local communities' capacity is also exacerbated by farmers leaving the agricultural sector to join Ukraine's armed forces, altering the workforce make-up and intensifying pressure on food production (Welsh, 2023). These economic, environmental, and social effects represent how the war has undermined SDGs 2 and 6 while also contributing to weakened community resilience and greater vulnerability to future shocks or disasters (SDG Target 11.5). These effects also influence various agents such as agricultural producers, farmers, citizens, consumers, and aquatic ecological communities through flows involving water, crops, money, infrastructure debris, and pollutants. These intracoupled effects lead to pericoupled and telecoupled effects that can be examined by assessing multiple systems.

One shock, multiple systems

Expanding the singular shock (i.e., Russia-Ukraine war) example to multiple systems in the MCF means encompassing the associated pericouplings and telecouplings connected with Ukraine's agri-food sector. The pericoupled and telecoupled receiving systems of interest are importing countries of Ukraine food exports (e.g., grains). Examples of major receiving systems are countries that rely on wheat imports from Ukraine: Bangladesh, Egypt, Indonesia, Lebanon, Morocco, Pakistan, Philippines, Tunisia, Turkey, and Yemen (Leal Filho et al., 2023). Similar to the one shock and one system combination above, the primary flows connecting Ukraine to these countries include movements of crops, food products, money, information, and people.

Food price spikes are a central effect of the war on Ukraine and its metacoupled countries. However, these price spikes represent a greater systemic disruption, also linked to rising energy costs, displacement of citizens, and reduced food availability (Hryhorczuk et al., 2024; Hryhoruk et al., 2021). Reduced food availability is characterized by diminished agricultural production, loss of storage capacity and livestock, and damaged infrastructure (Hryhorczuk et al., 2024). Trade flows have been disturbed, with many countries experiencing reduced imports from Ukraine. Ukraine is a major cereal producer in the Black Sea Region and prior to the war sent 98% of its grain exports through the Black Sea (Voicilas and Kalaman, 2020). Yet, the destruction and blockades by Russia on Ukrainian Black Sea ports have forced Ukraine. This reduction in Ukraine's grain export capacity has altered the flow of crops and products from Ukraine to some countries, with land routes unable to offset these obstacles. From 2021 to 2022, the value of cereal grain exports to countries adjacent to Ukraine (Belarus, Hungary, Moldova, Poland, Romania, Russia, and Slovakia) increased over 6,000%, from $40 million to $2.4 billion (USD), as Ukraine sought alternate routes for its exports (UN Comtrade, n.d.). Exports of grains from Ukraine to Romania saw the largest increase in value, roughly $1.3 billion from 2021 to 2022, and exports from Ukraine to Slovakia saw the largest percent increase. The increase in cereal market exports from Ukraine to other Eastern European countries is a result of the EU member states attempting to assuage the economic impact of the Russian invasion and blockades (Antoneac et al., 2023).

This widespread crop reduction in Ukraine's exports has prompted many countries to prioritize their own food security and sell their crops domestically to safeguard against price spikes (Osendarp et al., 2022; Polansek, 2022). Within 2 months of Russia's invasion of Ukraine, the number of countries imposing such export restrictions climbed from three to sixteen and further contributed to global crop price spikes (Lin et al., 2023; Glauber et al., 2022). Together these impacts on food access and availability directly hinder progress toward SDG 2 (Liu et al., 2023).

The Black Sea Grain Initiative (BSGI) was established after several months of exporting difficulties. The BSGI permitted the safe passage of Ukrainian exports through three key ports: Chornomorsk, Odesa, and Yuzhny/Pivdennyi. The initiative's main goal was to reduce the risk of escalating the global food crisis and prioritize limiting food price inflation as well as sending cargo to low-and lower-middle-income countries. Following the creation of the BSGI, global food prices decreased over five consecutive months and by about 23% since their peak in March 2022 (Leal Filho et al., 2023; Bizzarri, 2022).

The significant and abrupt impacts on Ukraine's interconnected food trade have led to research that links the preexisting vulnerabilities of the country to the intensity of the shock's impacts. For example, inefficient trade logistics already affecting Ukraine's export profitability (estimated to cost the industry between $0.6 and $1.6 billion annually) before the war were subsequently exacerbated by it (International Trade Administration, 2023). These complex dynamics highlight important components of temporal telecouplings to consider, such as time lags and legacy effects. Time lags represent the delayed onset of a shock's impacts; in this case, the time lag is characterized by Ukraine's underlying weaknesses accumulating over time and becoming evident after the war occurs. In the future, legacy effects such as war-related damage to infrastructure, trade routes, other institutions, and geopolitical tensions are likely to persist long after the shock. While it is difficult to recognize these cascading effects over time before they fully materialize, it is necessary to prevent further path dependencies that may indefinitely reduce a system's resilience and lead to greater vulnerability in the future.

This shock-system combination fits well when structured with the MCF. The MCF demonstrates how the effects (e.g., disruption of exports) influence agents (e.g., government actors) to utilize information flows and mitigate impacts in adjacent systems (e.g., importing countries) by maintaining sufficient flows of physical products (e.g., movement of goods). The response to the shock by agents, such as government actors, enacts policy like the BSGI (Bizzarri, 2022) to help strengthen system resilience and result in positive impacts on other systems' interconnected livelihoods.

Many agents affected at the intracoupled scale are similarly impacted in this combination, such as consumers, farmers, trade companies, and government actors. Intracoupled agents are directly involved with production, trade, and export capacity with policy action at the intracoupled scale focused on strengthening local governance, agricultural infrastructure, and shock relief mechanisms [e.g., Ukraine's State Programme provided over 77,000 loans to affected farming business entities, totaling approximately UAH 260.2 billion (Dorosh et al., 2024)]. At the pericoupled scale, regional governments and authorities coordinate policies and trade agreements to ensure the flow of food and goods or minimize risk [e.g., EU's Solidarity Lanes Initiative between Ukraine and its adjacent EU neighbors to improve regional trade overland (Directorate-General for Mobility and Transport, 2022)]. Lastly, at the telecoupled scale, international coalitions and humanitarian organizations implement widespread aid relief and policy interventions to mitigate food insecurity and help stabilize market prices [e.g., Black Sea Grain Initiative (Bizzarri, 2022)].

Since we expanded the scale of analyses to include pericoupled and telecoupled interactions, we noticed similar effects, such as food insecurity, inflation, and product scarcity, among neighboring and distant systems. Expanding the scale of analyses is important to fully see the reach of the shock's consequences and determine when or how agents should act. Initiatives such as those by the World Food Program or the BSGI can be implemented to relieve strain on the focal system and coupled systems. The magnitude of impacts may differ due to the unique attributes and vulnerability of each receiving system (e.g., country's GDP, average income level). The vulnerability of adjacent and distant countries is crucial in understanding how they will be affected by shocks. Then, such analyses can examine the commonalities between components of adjacent and distant systems (Tierney, 2019).

Multiple shocks, one system

By expanding the time of reference back to 2020, Ukraine's agri-food sector has experienced multiple shocks—the COVID-19 pandemic and the war. In the two sections above, we focused only on the war's couplings in the *one shock* combinations. Now, we use the MCF to examine how the pandemic's initial emergence 2 years prior weakened Ukraine's agri-food sector and supply chain, making it more vulnerable to impacts of the war. This demonstrates how changing the time of reference affects the interpretation of metacoupling interactions. These multiple shock combinations reveal that multifaceted shocks such as the pandemic and war have led to many socioeconomic and environmental effects in Ukraine and beyond. Analyzing multiple shocks using the MCF highlights how expanding the temporal lens can influence which effects are attributed to which causes and how compounding shocks contribute to reduced system resilience.

However, increasing the time frame and number of shocks being examined also increases the difficulty when distinguishing the effects of each shock. Organizing multiple shocks using the MCF helps identify pathways of vulnerability and increase understanding of the factors that influence systems' susceptibility to future shocks, especially when these shocks overlap in space and/or time, leading to compounding effects.

The shock of COVID-19 caused similar effects on Ukraine as the Russia-Ukraine war, such as disruptions throughout the food supply chain due to production shutdowns and other associated lockdowns, ultimately leading to significant spikes in food prices locally (Boyacı-Gündüz et al., 2021). These supply chain disruptions deterred progress toward SDG 2 by limiting the availability and affordability of nutritious food (Pereira et al., 2022). Potatoes and pork were the most affected food groups, with sugar and eggs also experiencing significant price increases of 46.2 and 30.4%, respectively (Vasylieva, 2021). The severe fluctuations in prices hindered access to certain food groups and balanced diets across the country, ultimately contributing to reduced livelihood and affecting a core component of SDG 2 (Pereira et al., 2022; Vasylieva, 2021).

The war further exacerbated food prices and intensified the threat of food shortages (Leal Filho et al., 2023). Crop production particularly suffered due to the war, with a significant loss of 7.58% in abandoned cropland and a staggering 33.02% in cultivated cropland in 2022 (He et al., 2023). As the war continues, rising cultivation costs and restrictions on grain transportation have caused huge losses to Ukraine's grain production. In the 2023–24 July–June season, Ukrainian grain exports experienced a significant decline of 29.7%, reaching 8.3 million metric tons—expected losses could exceed $3.2 billion (Polityuk, 2023). These threats to food security and sustainable water and land use hinder the achievements of SDG 2 and 6, while highlighting the importance of improving resilience of local food sectors to future shocks (SDG Target 11.5).

Multiple shocks have also placed severe strain on public health in Ukraine. As one of the nations with the weakest health systems in the post-Soviet Union countries, Ukraine's health system has demonstrated difficulty responding to outbreaks in an effective and timely manner (Kitamura et al., 2022; Matiashova et al., 2021). Before the broad-scale conflict in February of 2022, there had been 4.4 million COVID-19 infections in Ukraine since the beginning of the pandemic, resulting in 105,505 deaths (World Bank, Government of Ukraine, European Commission, 2022). The destruction of healthcare infrastructure and mass migration caused by the war further deteriorated public health in Ukraine, with many people migrating to western and southeastern parts of the country with poorer vaccination coverage (Mehta et al., 2023). It is generously estimated that about 4 million Ukrainians have emigrated from the country since the initial invasion and approximately 7 million people are internally displaced (Boyacı-Gündüz et al., 2021). Other challenges that the prevention and treatment of the COVID-19 pandemic faced were to its chronic care treatment and health prevention services (Patel and Erickson, 2022), which has further limited the population's capacity to maintain health and productivity.

The deterioration of public health during the pandemic directly limited labor availability, agricultural productivity, and food distribution, affecting Ukraine's agri-food sector significantly and delaying progress toward SDGs 2 and 3 (Good Health and Well-Being) given the notable health impacts. This shock-system combination reveals how multiple shocks' effects have propagated throughout social and economic dimensions in time and space, intertwining human well-being with food system resilience. The agents most affected in this combination are Ukrainian citizens, farmers, traders, and public health or service workers. In conclusion, the compounding effects of multiple shocks have strained Ukraine's vulnerable public health system and agri-food sector, leading to the need for rapid implementation of resilient remediation efforts in preparation for future shocks which can help fulfill SDG 11.

Multiple shocks, multiple systems

This combination encompasses the adjacent and distant systems connected with Ukraine's agri-food sector that are affected by COVID-19 and the war. The effects of multiple shocks extend beyond Ukraine, therefore, it is important to broaden the scope of reference. This combination illustrates all three types of couplings in the MCF with a focus on Ukraine's agri-food sector and demonstrates that while complexity may be minimized by isolating certain systems, important effects and feedback can be missed unless adjacent and distant systems are considered (Figure 3).

Worldwide, the COVID-19 pandemic had devastating effects on food security. Approximately 2.37 billion people were estimated to not have access to sufficient food in 2020 (Leal Filho et al., 2023). FAO reported that the Russia-Ukraine war has

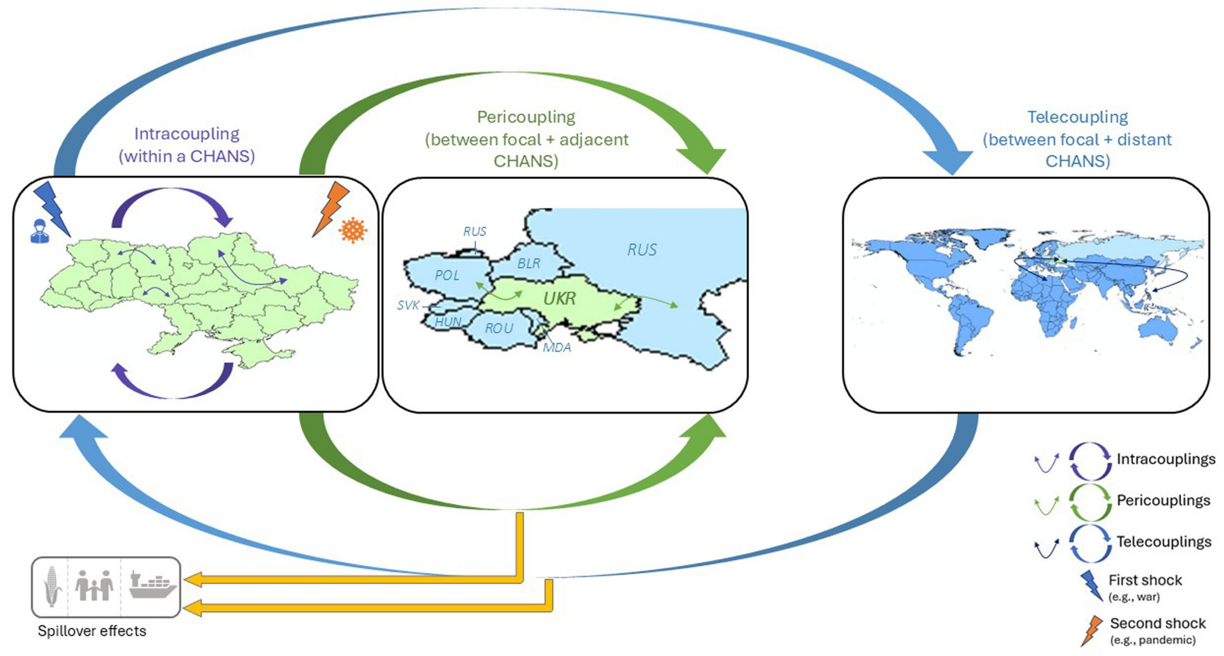

FIGURE 3
Conceptual diagram demonstrating multiple shocks (Russia-Ukraine war, COVID-19) and multiple systems under the metacoupling framework with Ukraine as the focal CHANS. Base maps created using Natural Earth (naturalearthdata.com).

further weakened food and energy markets globally that did not have a chance to fully recover from the pandemic (Leal Filho et al., 2023). This is a similar effect in these pericoupled and telecoupled systems to what we saw occurring within Ukraine at the intracoupled scale.

The hindrance of trade under major shocks such as the pandemic and war has far-reaching impacts. These ramifications affect pericoupled and telecoupled systems linked to Ukraine, as Ukraine's ability to export food to dependent countries is significantly diminished. The decline in the amount of food exports has threatened the food security of numerous countries, especially in the Middle East, North Africa, and the Sahel (Leal Filho et al., 2023; Behnassi and El Haiba, 2022). The Middle East and North Africa receive about a third of their cereal supplies from Ukraine, while East Africa depends on Ukraine for approximately 45% of their cereal imports (Leal Filho et al., 2023). Libya, Pakistan, Yemen, and Lebanon each source 30% of their wheat imports from Ukraine. The significant number of products that Ukraine supplies to these areas indicates that a substantial proportion of people are experiencing food insecurity, especially in already vulnerable countries (Leal Filho et al., 2023).

These cross-scale effects highlight the challenges of overcoming food insecurity to achieve SDG 2 at the global scale, where such crises can reverse progress in distant countries. The considerable increase in food prices further contributes to global food insecurity as a result of affected patterns of global trade (e.g., Black Sea), production, and consumption (Leal Filho et al., 2023). Farmers that depend on these crops for financial support are having their livelihoods disturbed and facing parallel economic insecurity to consumers affected by rising food prices. Currently, the FAO reports that approximately 600 million people worldwide will be undernourished in 2030. Compared to a scenario unaffected by either the pandemic or the Russia-Ukraine war, these shocks affect about 119 million more individuals (Leal Filho et al., 2023). Even if only the pandemic occurred and there were no war, an additional 23 million people would still be impacted (Leal Filho et al., 2023).

Another study examining the local and global impacts of the Russia-Ukraine war and the pandemic on agricultural sectors in the Netherlands demonstrates similar effects. Leal Filho et al. (2023) concluded that while the medium-term (2021–2025) impacts of the war that they examined were moderately limited, COVID-19 was also among the main factors leading to an increase in energy and agricultural commodity prices. As described in the *one system* combinations, the impacts experienced at the focal system level in Ukraine (e.g., food insecurity, diminished health and livelihood) are also seen in adjacent and distant systems affecting the same types of agents (e.g., consumers, farmers, public service workers). This exemplifies the ability of the metacoupling framework to compare similarities and differences between interconnected or parallel systems (e.g., countries). This combination also demonstrates the compounding impacts of both shocks, especially when systems have not had the chance to fully recover from one shock. Ultimately, these interconnected shocks illustrate the need for interdisciplinary and multisectoral collaboration between agents (e.g., government institutions, humanitarian organizations, aid relief groups) involved in international management of crises.

Shock-system combinations summary

Overall, our shock-system combinations demonstrate how the MCF can help identify similar and different social, economic, and environmental impacts on many systems when the scope is expanded to encompass multiple systems and shocks. They also highlight interconnected relationships and feedback mechanisms that may not be considered at the intracoupled scale.

Many similarities and differences exist at different scales of multiple shocks. Across all combinations, there are significant environmental effects revolving around environmental degradation (e.g., deforestation, habitat destruction, and increased greenhouse gas emissions). While the intracoupling combinations (i.e., one system) focus on localized effects like farmland degradation, wildfires, and water contamination, the peri-and telecoupling combinations (i.e., multiple systems) emphasize broader impacts such as deforestation, unsustainable resource practices and risk of disease transmission from wildlife to humans. These health risks are intertwined with other social effects seen with multiple shocks and systems such as overburdened healthcare and diminished livelihoods. Food insecurity is experienced across all combinations, while unsanitary living conditions and deteriorated healthcare infrastructure occur most predominantly in the intracoupling combinations. Weakened economic development, disrupted supply chains, increased unemployment rates, and changes in consumption patterns are revealed to affect multiple systems under multiple shocks. Overall, examining multiple systems encompasses broader global effects that may generate feedback and exacerbate localized impacts in a focal system, especially given multiple shocks. For a categorized summary of each type of effect by combination, see Table 3.

Challenges and opportunities

The metacoupling framework contributes to the understanding of multiple shocks across multiple systems and scales. However, some important limitations need to be addressed in future work. While the MCF can provide a structured approach to examining complex interactions between systems, their boundaries remain interconnected and nested in nature, requiring the use of quantitative analyses to measure the magnitude of the impact of multiple shocks. Our approach using the MCF is intended to disentangle the multiple scales and interdependent linkages across which shocks disseminate to visualize relational complexity, without neglecting the inherent nested and nonlinear structure of CHANS. Ukraine's global agri-food sector is highly networked with multi-directional flows and feedbacks. Therefore, rather than isolating these relationships and implying strict boundaries, the MCF provides a heuristic structure that unravels the complexity into digestible components. Our method of analyzing one system versus multiple systems can also provide a starting point for understanding where management interventions may be most effective across scales, even within a globally integrated network.

Attributing causality to phenomena in such a globally integrated system poses further challenges (Busck-Lumholt et al., 2022). Quantifying and separating the impact of a single shock is difficult within a set of interconnected systems. More work is needed in metacoupling to address causality by developing robust linkages between coupled systems' components. We use observational data in this study, thus, the isolated impact of a given shock is obscured by elements of complex systems, such as time lags, feedback loops, and nonlinearities (Liu et al., 2013). Future research can build on this conceptualization by incorporating these elements as well as spillover systems to fully capture the nonlinearity of multiple shocks. More work could be done to quantify the complex reactions of systems to shocks using novel methods such as network science (Carlson et al., 2021; Naqvi and Monasterolo, 2021), life cycle assessment (Giusti et al., 2023), or computable general equilibrium models (Xie et al., 2014; Haqiqi et al., 2023).

Many pathways exist for future analyses of spillover systems and can be examined using the combination structure and the MCF that we have described here. For example, technology and knowledge transfers were found to be the third most common type of flow in metacoupling literature (Li et al., 2023). This flow is represented by the Russia-Ukraine war; the use of drones in Ukraine is being mirrored by Taiwan as Taiwan prepares for a potential war with China (Wang, 2024; The Wall Street Journal, 2024a). This demonstrates a spillover system where the flow of knowledge influences a region not directly connected to the sending or receiving system.

Another important spillover system that can be added to the quantification of the MCF is examining the EU's natural gas supply. Following the initial Russian invasion, the EU imposed economic sanctions on Russia (Wallace and Kantchev, 2022). Russia countered by reducing gas flows to Europe, citing technical or contractual reasons. This caused natural gas prices to spike due to the uncertainties surrounding the natural gas supply (Blakeway et al., 2024). The EU has moved to diversify its energy sources to reduce reliance on Russian gas, stabilize its stock, and enhance its energy security. This sequence of events has created spillover systems in the countries experiencing high energy costs as well as the countries that the EU has drawn on to diversify its energy sources (Wallace and Kantchev, 2022). Further ecological and economic spillovers may result from Russia's attempts to circumvent EU sanctions and possibly use unsafe methods for transporting energy, increasing the likelihood of oil spills in international waters (The Wall Street Journal, 2024b).

The complex and cross-scale interconnections between coupled human and natural systems present significant challenges when tracing the origins and effects of individual shocks, which become more pronounced when evaluating the consequences of multiple shocks. Failing to consider multiple systems and scales may lead to misleading conclusions when distinguishing between the effects of singular and multiple shocks.

Addressing the intricacy associated with spatial and temporal dimensions of multiple shocks requires the use of an interdisciplinary and multiscale framework such as the MCF that encompasses focal, adjacent, and distant systems, as well as their interrelationships. Although previous research has investigated spatial (linkages across space) and temporal (linkages across time) telecouplings together (Friis and Nielsen, 2017; Montti et al., 2024; Liu, 2023), most telecoupling research has emphasized spatial dimensions. While we emphasize the role of specific temporal telecouplings such as time lags and legacy effects here, future metacoupling research would benefit from focusing on temporal dimensions and how the onset of effects from past events influences future conditions in other systems.

Actionable recommendations and strategies

Here, we suggest several recommendations and strategies to build agri-food sector resilience to multiple shocks.

First, diversify production and trade partners. Murphy et al. (2023) found that the features of agri-food sectors that were critical to improving resilience are diversity and decentralization. Reducing countries' overreliance on a limited number of export/import routes and partners can alleviate the impact of such a major exporter, like Ukraine, suffering multiple shocks (Murphy et al., 2023). Greater diversity and decentralization in agri-food sectors helps reduce risk and maintain basic system functioning during multiple shocks (Coopmans et al., 2021). However, diversification and decentralization can be accompanied by short-term economic costs that require substantial investment up front.

Second, combine short and long supply chains. Shorter supply chains are flexible and able to adapt more quickly, while long supply chains can reduce costs, increase market reach, and access more resources from distant regions (Murphy et al., 2023). Integrating both long and short supply chains can balance global impact with local stability, enhancing the resilience of agri-food sectors and supporting food security in response to shocks. A mixed strategy that can flexibly adapt to the necessary risk context and type of shock is ideal (Coopmans et al., 2021). For example, shorter chains may be more beneficial during global shocks (e.g., pandemic), while dependence on nearby production may increase risk during local or regional shocks (e.g., extreme weather) (El Korchi, 2022).

Third, invest in and encourage the development of local to regional food markets and infrastructure. Such development can further reduce the vulnerability of agri-food sectors during global shocks and promote domestic food security (Murphy et al., 2023). Similarly to diversification and decentralization, overreliance on local production may cause instability due to local markets' sensitivity to climate and resource limitations. Thus, investment in local infrastructure and markets should be accompanied by risk assessments that consider these factors.

Fourth, implement adaptive governance that applies the metacoupling framework. This approach can improve the recognition and management of cross-scale and cross-system interactions. By highlighting the interdependence of distant systems, the MCF encourages interdisciplinary and multisectoral coordination in responding to complex multiple shocks (Murphy et al., 2023; Coopmans et al., 2021). Still, the implementation of metacoupling-guided governance faces potential institutional and political challenges, such as conflicting priorities and data-sharing limitations (Zhao et al., 2024).

The effectiveness of these collective strategies relies on scale, context, and timing. Accounting for the potential tradeoffs of each strategy can enhance the robustness of local and global management, while designing secure and equitable agri-food sectors in the face of multiple shocks (Zhao et al., 2024).

Conclusion

Our work proposes a collection of ways to conceptually understand single and multiple shocks to one or many coupled human and natural systems. Applications of the MCF could serve as a method for untangling the complexity of single and/or multiple shocks across single and/or multiple systems.

The MCF is a useful addition to shock research because it enables a systematic study of interactions happening locally, nearby, and globally. While there are drawbacks of accounting for such complex and interrelated components and systems, such benefits of the MCF may include informed policy (e.g., BSGI) and multi-sectoral collaboration to strengthen system resilience proactively rather than reactively. These approaches can directly contribute to the transformative change needed to promote resilient agri-food sectors and tackle the United Nations SDGs (FAO, 2021; United Nations, 2015).

Employing the MCF to examine multiple shocks can yield essential foundational information into contemporary issues involving numerous social, environmental, and economic factors, or for those not yet viewed through such an interdisciplinary lens. Future research can continue to evaluate underlying vulnerability and resilience, and how vulnerability and resilience influence a system's response to the presence or absence of shocks using the MCF. Since this study is the first of its kind to examine multiple shocks with the MCF, it demonstrates an initial application but also leaves much to explore regarding how the MCF can be applied to other shocks across multiple systems worldwide.

Author contributions

SW: Writing – original draft, Project administration, Visualization, Methodology, Conceptualization, Writing – review & editing. NM: Visualization, Formal analysis, Data curation, Methodology, Conceptualization, Writing – review & editing, Writing – original draft. MR: Writing – review & editing, Visualization, Conceptualization, Writing – original draft, Methodology. XY: Writing – original draft, Visualization, Conceptualization. JH: Writing – original draft, Visualization, Conceptualization. NJ: Writing – original draft, Formal analysis, Data curation, Conceptualization. JL: Methodology, Conceptualization, Supervision, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This work was financially supported by the USDA NIFA (2023-68012-39076), NSF (award numbers 2033507 and 2118329), and Michigan AgBioResearch.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Allam, Z., Bibri, S. E., and Sharpe, S. A. (2022). The rising impacts of the COVID-19 pandemic and the Russia–Ukraine war: energy transition, climate justice, global inequality, and supply chain disruption. *Resources* 11:99. doi: 10.3390/resources11110099

Antoneac, AL, Petre, IL, Iana, AS, Antoneac (lungu), A, Petre, IL, Iana, AS, et al. Assessing the Implications of the Russia-Ukraine Military Conflict on Romania's Grain Trade Dynamics. (2023); Available online at: https://www.acadlore.com/article/JGELCD/2023_2_2/jgelcd020204 (Accessed February 21, 2024).

Bănică, A., Kourtit, K., and Nijkamp, P. (2020). Natural disasters as a development opportunity: a spatial economic resilience interpretation. *Rev. Reg. Res.* 40, 223–249. doi: 10.1007/s10037-020-00141-8

Banks, S. C., Cary, G. J., Smith, A. L., Davies, I. D., Driscoll, D. A., Gill, A. M., et al. (2013). How does ecological disturbance influence genetic diversity? *Trends Ecol. Evol.* 28, 670–679. doi: 10.1016/j.tree.2013.08.005

Barbieri, P., Mac Donald, G. K., Bernard de Raymond, A., and Nesme, T. (2022). Food system resilience to phosphorus shortages on a telecoupled planet. *Nat Sustain.* 5, 114–122. doi: 10.1038/s41893-021-00816-1

Behnassi, M., and El Haiba, M. (2022). Implications of the Russia–Ukraine war for global food security. *Nat. Hum. Behav.* 6, 754–755. doi: 10.1038/s41562-022-01391-x

Bizzarri, G. The Black Sea Grain Initiative: What it is, and why it's important for the world. United Nations. (2022); Available online at: https://news.un.org/en/story/2022/09/1126811

Blakeway, A, Jalan, S, and Seth, T. European LNG prices reach five-month high as global competition heats up [Internet]. (2024). Available online at: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/lng/052224-european-lng-prices-reach-five-month-high-as-global-competition-heats-up (Accessed June 25, 2024).

Boyacı-Gündüz, C. P., Ibrahim, S. A., Wei, O. C., and Galanakis, C. M. (2021). Transformation of the food sector: security and resilience during the COVID-19 pandemic. *Foods* 10:497. doi: 10.3390/foods10030497

Busck-Lumholt, L. M., Coenen, J., Persson, J., Frohn Pedersen, A., Mertz, O., and Corbera, E. (2022). Telecoupling as a framework to support a more nuanced understanding of causality in land system science. *J. Land Use Sci.* 17, 386–406. doi: 10.1080/1747423X.2022.2086640

Carlson, A. K., Taylor, W. W., and Hughes, S. M. (2020b). The metacoupling framework informs stream salmonid management and governance. *Front. Environ. Sci.* 8:27. doi: 10.3389/fenvs.2020.00027

Carlson, A. K., Taylor, W. W., Rubenstein, D. I., Levin, S. A., and Liu, J. (2020a). Global marine fishing across space and time. *Sustainability* 12:4714. doi: 10.3390/su12114714

Carlson, A. K., Young, T., Centeno, M. A., Levin, S. A., and Rubenstein, D. I. (2021). Boat to bowl: resilience through network rewiring of a community-supported fishery amid the COVID-19 pandemic. *Environ. Res. Lett.* 16:034054. doi: 10.1088/1748-9326/abe4f6

Chai, L., Liu, A., Li, X., Guo, Z., He, W., Huang, J., et al. (2024). Telecoupled impacts of the Russia–Ukraine war on global cropland expansion and biodiversity. *Nat. Sustain.* 7, 432–441. doi: 10.1038/s41893-024-01292-z

Choudhary, O. P., Saied, A. A., Priyanka, Ali, R. K., and Maulud, S. Q. (2022). Russo-Ukrainian war: an unexpected event during the COVID-19 pandemic. *Travel Med. Infect. Dis.* 48:102346. doi: 10.1016/j.tmaid.2022.102346

Coopmans, I., Bijttebier, J., Marchand, F., Mathijs, E., Messely, L., Rogge, E., et al. (2021). COVID-19 impacts on Flemish food supply chains and lessons for Agri-food system resilience. *Agric. Syst.* 190:103136. doi: 10.1016/j.agsy.2021.103136

da Silva, R. F. B., Viña, A., de Castro Victoria, D., Batistella, M., Martha, G. B. Jr., Moran, E. F., et al. (2025). Compound effects of drought and COVID-19 on soybean production in Brazil: Challenges and policy responses. *Sci. Total Environ.* 971:179047. doi: 10.1016/j.scitotenv.2025.179047

da Silva, R. F. B., Viña, A., Moran, E. F., Dou, Y., Batistella, M., and Liu, J. (2021). Socioeconomic and environmental effects of soybean production in metacoupled systems. *Sci. Rep.* 11:18662. doi: 10.1038/s41598-021-98256-6

Directorate-General for Mobility and Transport. European Commission to establish solidarity lanes to help Ukraine export agricultural goods. (2022); Available online at: https://transport.ec.europa.eu/news-events/news/european-commission-establish-solidarity-lanes-help-ukraine-export-agricultural-goods-2022-05-12_en

Dominey-Howes, D. (2018). Hazards and disasters in the Anthropocene: some critical reflections for the future. *Geosci. Lett.* 5:7. doi: 10.1186/s40562-018-0107-x

Dorosh, O, Kupriianchyk, I, Dorosh, Y, and Butenko, Y. Ukrainian agriculture in times of war: analysis of support programmes. Stud. Agr. Econ.. (2024). Available online at: https://studies.hu/ukrainian-agriculture-in-times-of-war-analysis-of-support-programmes/ (Accessed October 15, 2025).

Drake, J. M., Marty, É., Gandhi, K. J. K., Welch-Devine, M., Bledsoe, B., Shepherd, M., et al. (2023). Disasters collide at the intersection of extreme weather and infectious diseases. *Ecol. Lett.* 26, 485–489. doi: 10.1111/ele.14188

Dvigun, A., Datsii, O., Levchenko, N., Shyshkanova, G., and Dmytrenko, R. (2022). Rational use of fresh water as a guarantee of agribusiness development in the context of the exacerbated climate crisis. *Sci. Innov.* 18, 85–99. doi: 10.15407/scine18.02.085

El Korchi, A. (2022). Survivability, resilience and sustainability of supply chains: the COVID-19 pandemic. *J. Clean. Prod.* 377:134363. doi: 10.1016/j.jclepro.2022.134363

FAO (2021). The state of food and agriculture 2021. Making Agrifood systems more resilient to shocks and stresses. Rome: Food and Agriculture Organization of the United Nations.

Friis, C, and Nielsen, J. Land-use change in a telecoupled world: the relevance and applicability of the telecoupling framework in the case of banana plantation expansion in Laos. Ecol. Soc.. (2017); 22. Available online at: https://www.ecologyandsociety.org/vol22/iss4/art30/

Giusti, G., Galo, N. R., Tóffano Pereira, R. P., Lopes Silva, D. A., and Filimonau, V. (2023). Assessing the impact of drought on carbon footprint of soybean production from the life cycle perspective. *J. Clean. Prod.* 425:138843. doi: 10.1016/j.jclepro.2023.138843

Glauber, J, Laborde, D, and Mamun, A. From bad to worse: How Ukraine-Russia war-related export restrictions exacerbate global food insecurity. International Food Policy Research Institute. (2022); Available online at: https://www.ifpri.org/blog/bad-worse-how-export-restrictions-exacerbate-global-food-security

Gleick, P., Vyshnevskyi, V., and Shevchuk, S. (2023). Rivers and water systems as weapons and casualties of the Russia-Ukraine war. *Earths Future* 11:e2023EF003910. doi: 10.1029/2023EF003910

Haqiqi, I., Grogan, D. S., Horeh, M. B., Liu, J., Baldos, U. L. C., Lammers, R., et al. (2023). Local, regional, and global adaptations to a compound pandemic-weather stress event. *Environ. Res. Lett.* 18:035005. doi: 10.1088/1748-9326/acbbe3

He, T., Zhang, M., Xiao, W., Zhai, G., Wang, Y., Guo, A., et al. (2023). Quantitative analysis of abandonment and grain production loss under armed conflict in Ukraine. *J. Clean. Prod.* 412:137367. doi: 10.1016/j.jclepro.2023.137367

Hryhorczuk, D., Levy, B. S., Prodanchuk, M., Kravchuk, O., Bubalo, N., Hryhorczuk, A., et al. (2024). The environmental health impacts of Russia's war on Ukraine. *J. Occup. Med. Toxicol.* 19:1. doi: 10.1186/s12995-023-00398-y

Hryhoruk, P., Khrushch, N., Grygoruk, S., Gorbatiuk, K., and Prystupa, L. (2021). Assessing the impact of COVID-19 pandemic on the regions' socio-economic development: the case of Ukraine. *EJSD* 10:63. doi: 10.14207/ejsd.2021.v10n1p63

International Trade Administration. Ukraine-country commercial Guide. (2023). Available online at: https://www.trade.gov/country-commercial-guides/ukraine-agribusiness

Jia, N., Xia, Z., Li, Y., Yu, X., Wu, X., Li, Y., et al. (2024). The Russia-Ukraine war reduced food production and exports with a disparate geographical impact worldwide. *Commun. Earth Environ.* 5:765. doi: 10.1038/s43247-024-01915-5

Jiang, Q, Xu, Z, Cui, Y, and Liu, J. Complex impacts of wars on global sustainable development in a metacoupled world. I-GUIDE Forum [Internet]. (2023); Available online at: https://docs.lib.purdue.edu/iguide/2023/presentations/12

Kapsar, K., Frans, V. F., Brigham, L. W., and Liu, J. (2022). The metacoupled Arctic: human–nature interactions across local to global scales as drivers of sustainability. *Ambio* 51, 2061–2078. doi: 10.1007/s13280-022-01729-9

Kholoshyn, I, Mantulenko, S, Joyce, AS, Sherick, D, Uvaliev, T, and Vedmitska, V Geography of agricultural exports from Ukraine S Semerikov, S Chukharev, S Sakhno, A Striuk, A Iatsyshyn and S Klimovet al., editors E3S Web of Conferences (2021) 280 11009.

Kitamura, N., Abbas, K., and Nathwani, D. (2022). Public health and social measures to mitigate the health and economic impact of the COVID-19 pandemic in Turkey, Egypt, Ukraine, Kazakhstan, and Poland during 2020–2021: situational analysis. *BMC Public Health* 22:991. doi: 10.1186/s12889-022-13411-6

Leal Filho, W., Fedoruk, M., Paulino Pires Eustachio, J. H., Barbir, J., Lisovska, T., Lingos, A., et al. (2023). How the war in Ukraine affects food security. *Foods* 12:3996. doi: 10.3390/foods12213996

Li, Y., Jia, N., Yu, X., Manning, N., Lan, X., and Liu, J. (2023). Transboundary flows in the metacoupled Anthropocene: typology, methods, and governance for global sustainability. *Ecol. Soc.* 28:art19. doi: 10.5751/ES-14351-280319

Lin, F., Li, X., Jia, N., Feng, F., Huang, H., Huang, J., et al. (2023). The impact of Russia-Ukraine conflict on global food security. *Glob. Food Secur.* 36:100661. doi: 10.1016/j.gfs.2022.100661

Liobikienė, G., Matiiuk, Y., and Krikštolaitis, R. (2023). The concern about main crises such as the Covid-19 pandemic, the war in Ukraine, and climate change's impact on energy-saving behavior. *Energy Policy* 180:113678. doi: 10.1016/j.enpol.2023.113678

Liu, J. Integration across a metacoupled world. Ecol. Soc.. (2017); 22. Available online at: https://www.jstor.org/stable/26799024

Liu, J. (2023). Leveraging the metacoupling framework for sustainability science and global sustainable development. *Natl. Sci. Rev.* 10:nwad090. doi: 10.1093/nsr/nwad090

Liu, J., Balmford, A., and Bawa, K. S. (2022). Fuel, food and fertilizer shortage will hit biodiversity and climate. *Nature* 604:425. doi: 10.1038/d41586-022-01061-y

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., et al. (2007). Complexity of coupled human and natural systems. *Science* 317, 1513–1516. doi: 10.1126/science.1144004

Liu, J, Hull, V, Batistella, M, DeFries, R, Dietz, T, Fu, F, et al Framing sustainability in a telecoupled world. Ecol. Soc. (2013);18. Available online at: https://www.jstor.org/stable/26269331

Liu, J., and Viña, A. (2014). Pandas, Plants, and People. Annals of the Missouri Botanical Garden. 100, 108–125. doi: 10.3417/2013040

Liu, L., Wang, W., Yan, X., Shen, M., and Chen, H. (2023). The cascade influence of grain trade shocks on countries in the context of the Russia-Ukraine conflict. *Humanit. Soc. Sci. Commun.* 10:449. doi: 10.1057/s41599-023-01944-z

Machlis, G. E., Román, M. O., and Pickett, S. T. A. (2022). A framework for research on recurrent acute disasters. *Sci. Adv.* 8. doi: 10.1126/sciadv.abk2458

Martinho, V. J. P. D. (2022). Impacts of the COVID-19 pandemic and the Russia–Ukraine conflict on land use across the world. *Land* 11:1614. doi: 10.3390/land11101614

Matiashova, L., Isayeva, G., Shanker, A., Tsagkaris, C., Aborode, A. T., Essar, M. Y., et al. (2021). COVID-19 vaccination in Ukraine: an update on the status of vaccination and the challenges at hand. *J. Med. Virol.* 93, 5252–5253. doi: 10.1002/jmv.27091

Mayer, A., Martín-López, B., Locatelli, B., Rabeschini, G., Liu, J., Loos, J., et al. (2025). A metacoupling lens on the co-production of nature's contributions to people: insights for sustainability. *Adv. Ecol. Res.* 72, 91–115. doi: 10.1016/bs.aecr.2025.02.001

Mehta, N. K., Honchar, I., Doroshenko, O., Pak, K., Daniuk, M., and Polikarchuk, P. (2023). Impact of the COVID-19 pandemic on Ukrainian mortality, 2020–2021. *PLoS One* 18:e0285950. doi: 10.1371/journal.pone.0285950

Merz, L., Yang, D., and Hull, V. (2020). A metacoupling framework for exploring transboundary watershed management. *Sustainability* 12:1879. doi: 10.3390/su12051879

Montti, L., Gasparri, N. I., and Grau, H. R. (2024). Telecoupling lens for integrating ecological and human dimensions of the biological invasion problem. *Sustain. Sci.* 19, 1139–1154. doi: 10.1007/s11625-024-01476-8

Murphy, M., Carey, R., and Alexandra, L. (2023). Building the resilience of Agri-food systems to compounding shocks and stresses: a case study from Melbourne, Australia. *Front. Sustain. Food Syst.* 7:1130978. doi: 10.3389/fsufs.2023.1130978

Naqvi, A., and Monasterolo, I. (2021). Assessing the cascading impacts of natural disasters in a multi-layer behavioral network framework. *Sci. Rep.* 11:20146. doi: 10.1038/s41598-021-99343-4

National Academies of Sciences, Engineering, and Medicine. A vision for continental-scale biology: research across multiple scales [internet]. Washington, D.C.: National Academies Press; (2025). Available online at: https://nap.nationalacademies.org/catalog/27285 (Accessed October 11, 2025).

Nchasi, G., Mwasha, C., Shaban, M. M., Rwegasira, R., Mallilah, B., Chesco, J., et al. (2022). Ukraine's triple emergency: food crisis amid conflicts and COVID-19 pandemic. *Health Sci. Rep.* 5:e862. doi: 10.1002/hsr2.862

Osendarp, S., Verburg, G., Bhutta, Z., Black, R. E., De Pee, S., Fabrizio, C., et al. (2022). Act now before Ukraine war plunges millions into malnutrition. *Nature* 604, 620–624. doi: 10.1038/d41586-022-01076-5

Patel, S. S., and Erickson, T. B. (2022). The new humanitarian crisis in Ukraine: coping with the public health impact of hybrid warfare, mass migration, and mental health trauma. *Disaster Med. Public Health Prep.* 16, 2231–2232. doi: 10.1017/dmp.2022.70

Pereira, P., Bašić, F., Bogunovic, I., and Barcelo, D. (2022). Russian-Ukrainian war impacts the total environment. *Sci. Total Environ.* 837:155865. doi: 10.1016/j.scitotenv.2022.155865

Pescaroli, G., and Alexander, D. A. (2015). A definition of cascading disasters and cascading effects: Going beyond the "toppling dominos" metaphor. *Planet@ risk*, Davos: Global Risk Forum GRF Davos. 2, 58–67.

Piquer-Rodríguez, M., Friis, C., Andriatsitohaina, R. N. N., Boillat, S., Roig-Boixeda, P., Cortinovis, C., et al. (2023). Global shocks, cascading disruptions, and (re-)connections: viewing the COVID-19 pandemic as concurrent natural experiments to understand land system dynamics. *Landsc. Ecol.* 38, 1147–1161. doi: 10.1007/s10980-023-01604-2

Polansek, T. Droughts, Ukraine war push global grain stocks toward worrying decade low. Reuters [Internet]. (2022); Available online at: https://www.reuters.com/markets/commodities/droughts-ukraine-war-push-global-grain-stocks-toward-worrying-decade-low-2022-09-26/

Polityuk, P. Ukraine's farmers look to new Black Sea route to boost food exports. The Economic Times. (2023); Available online at: https://economictimes.indiatimes.com/small-biz/trade/exports/insights/ukraines-farmers-look-to-new-black-sea-route-to-boost-food-exports/articleshow/104668525.cms

Sadłowski, A., Brdulak, J., and Budzyńska, A. (2023). The transport of Ukrainian grain through Poland and the domestic grain market. *Humanit. Soc. Sci. Q.* 30, 109–119. doi: 10.7862/rz.2023.hss.19

Shumilova, O., Tockner, K., Sukhodolov, A., Khilchevskyi, V., De Meester, L., Stepanenko, S., et al. (2023). Impact of the Russia–Ukraine armed conflict on water resources and water infrastructure. *Nat Sustain.* 6, 578–586. doi: 10.1038/s41893-023-01068-x

The Economist. Russia's explosion of a huge Ukrainian dam had surprising effects; Available online at: https://www.economist.com/interactive/europe/2024/06/05/russias-explosion-of-a-huge-ukrainian-dam-had-surprising-effects (Accessed June 19, 2024).

The Wall Street Journal. (2024a). Exclusive | How Ukraine's naval drones turned the tide in the battle of the Black Sea. Available online at: https://www.wsj.com/world/naval-drones-innovation-warfare-ukraine-russia-ce35adfa (Accessed June 25, 2024).

The Wall Street Journal. (2024b). Russia taps unlikely allies to help ship sanctioned oil. Available online at: https://www.wsj.com/world/how-a-shadow-fleet-of-ancient-tankers-keeps-russian-oil-flowing-e667b395 (Accessed June 25, 2024).

Tierney, K. (2019). Disasters: a sociological approach, Cambridge, UK; Medford, MA: Polity Press.

Torres, A., Jouffray, J. B., Van Lancker, V., Velpen, A. V., and Liu, J. (2025). Reducing sand mining's growing toll on marine biodiversity. *One Earth* 8:101202. doi: 10.1016/j.oneear.2025.101202

UN Comtrade. Available online at: https://comtradeplus.un.org/ (Accessed June 19, 2024).

United Nations. Sendai framework for disaster risk reduction 2015–2030. Japan: United Nations; (2015). Available online at: https://sdgs.un.org/sites/default/files/publications/2157sendaiframeworkfordrren.pdf

van Meijl, H., Bartelings, H., van Berkum, S., Cui, H. D., Kristkova, Z. S., and van Zeist, W. J. (2024). The Russia-Ukraine war decreases food affordability but could reduce global greenhouse gas emissions. *Commun Earth Environ.* 5, 1–12. doi: 10.1038/s43247-024-01208-x

Vasylieva, N. Food security in times of Covid-19: price aspects in Ukraine and neighboring EU countries Monten. J. Econ. (2021) 17 21–30. Available online at: https://mnje.com/sites/mnje.com/files/021-030-_natalia_vasylieva_-_w.u._-_rrr.pdf

Viña, A., Bearer, S., Chen, X., He, G., Linderman, M., An, L., et al. (2007). Temporal changes in Giant panda habitat connectivity across boundaries of Wolong nature reserve, China. *Ecol. Appl.* 17, 1019–1030. doi: 10.1890/05-1288

Viña, A., Chen, X., McConnell, W. J., Liu, W., Xu, W., Ouyang, Z., et al. (2011). Effects of natural disasters on conservation policies: the case of the 2008 Wenchuan earthquake, China. *Ambio* 40, 274–284. doi: 10.1007/s13280-010-0098-0

Voicilas, D. M., and Kalaman, O. (2020). Cereal market in the Black Sea region - comparative analysis for Romania and Ukraine. *Agric. Econ. Rural Dev.* 17, 183–198.

Vyshnevskyi, V., Shevchuk, S., Komorin, V., Oleynik, Y., and Gleick, P. (2023). The destruction of the Kakhovka dam and its consequences. *Water Int.* 48, 631–647. doi: 10.1080/02508060.2023.2247679

Walker, B, Carpenter, S, Rockstrom, J, Crépin, AS, and Peterson, G. Drivers, "slow" variables, "fast" variables, shocks, and resilience. Ecol. Soc.. (2012);17. Available online at: https://www.ecologyandsociety.org/vol17/iss3/art30/

Wallace, J, and Kantchev, G. Russia slashes gas flows, aiming economic weapon at Europe. Wall Street J.. (2022). Available online at: https://www.wsj.com/articles/russia-slashes-gas-flows-aiming-economic-weapon-at-europe-11655393254 (Accessed June 25, 2024).

Wang, J.. (2024). Taiwan wants a drone army—but China makes the drones it wants. Available online at: https://www.wsj.com/world/taiwan-drone-stockpiling-efforts-bcf70ef5 (Accessed June 25, 2024).

Welsh, C. Russia, Ukraine, and Global Food Security: A One-Year Assessment. CSIS: Center for Strategic and International Studies. (2023). Available online at: https://www.csis.org/analysis/russia-ukraine-and-global-food-security-one-year-assessment

World Bank, Government of Ukraine, European Commission. (2022). The COVID-19 Crisis in Ukraine [Internet]. Organization for Economic Cooperation and Development; (Ukraine Rapid Damage and Needs Assessment August 2022). Available online at: https://documents1.worldbank.org/curated/en/099445209072239810/pdf/P17884304837910630b9c6040ac12428d5c.pdf (Accessed August 16, 2022).

Xie, W., Li, N., Li, C., Wu, J., dong, Hu, A., et al. (2014). Quantifying cascading effects triggered by disrupted transportation due to the great 2008 Chinese ice storm: implications for disaster risk management. *Nat. Hazards* 70, 337–352. doi: 10.1007/s11069-013-0813-9

Xu, Z., Li, Y., Chau, S. N., Dietz, T., Li, C., Wan, L., et al. (2020). Impacts of international trade on global sustainable development. *Nat. Sustain.* 3, 964–971. doi: 10.1038/s41893-020-0572-z

Yang, W., Dietz, T., Kramer, D. B., Ouyang, Z., and Liu, J. (2015). An integrated approach to understanding the linkages between ecosystem services and human well-being. *Ecosyst. Health Sustain.* 1, 1–12. doi: 10.1890/EHS15-0001.1

Yang, W., Viña, A., Dietz, T., Kramer, D. B., Ouyang, Z., and Liu, J. (2016). "Vulnerability and adaptation to natural disasters" in Pandas and people: coupling human and natural Systems for Sustainability (Oxford: Oxford University Press), 148–158.

Zhang, J, Connor, T, Yang, H, Ouyang, Z, Li, S, and Liu, J. Complex effects of natural disasters on protected areas through altering telecouplings. Ecol. Soc.. (2018); 23. Available online at: https://www.ecologyandsociety.org/vol23/iss3/art17/

Zhao, G., Vazquez-Noguerol, M., Liu, S., and Prado-Prado, J. C. (2024). Agri-food supply chain resilience strategies for preparing, responding, recovering, and adapting in relation to unexpected crisis: a cross-country comparative analysis from the COVID-19 pandemic. *J. Bus. Logist.* 45:e12361. doi: 10.1111/jbl.12361