

Shock propagation from the Russia–Ukraine conflict on international multilayer food production network determines global food availability

Received: 4 October 2022

Accepted: 10 May 2023

Published online: 15 June 2023

 Check for updates

Moritz Laber ^{1,2}, Peter Klimek ^{1,3,4}, Martin Bruckner ^{5,6}, Liuhuyang Yang ¹ & Stefan Thurner ^{1,3,4,7} 

Dependencies in the global food production network can lead to shortages in numerous regions, as demonstrated by the impacts of the Russia–Ukraine conflict on global food supplies. Here we reveal the losses of 125 food products after a localized shock to agricultural production in 192 countries and territories using a multilayer network model of trade (direct and conversion of food products (indirect)), thereby quantifying 10^8 shock transmissions. We find that a complete agricultural production loss in Ukraine has heterogeneous impacts on other countries, causing relative losses of up to 89% in sunflower oil and 85% in maize via direct effects and up to 25% in poultry meat via indirect impacts. Whereas previous studies often treated products in isolation and did not account for product conversion during production, the present model considers the global propagation of local supply shocks along both production and trade relations, allowing for a comparison of different response strategies.

Trade relations among countries create a global network^{1–7}. This trade network facilitates the propagation of locally confined shocks in the food system around the globe^{7–11}. Such shocks can result from a variety of often overlapping causes, most notably extreme weather events or economic and geopolitical crises^{12–14}, and they have been found to become more frequent over time¹³. Building dynamical models of shock propagation^{15–20} makes it possible to assess the effect of a locally confined event on the economy in distant places and to compare different response strategies^{16,19}. These modelling efforts have highlighted that the set of affected countries extends beyond direct trading partners¹⁸ and that countries differ in their ability to deal with shocks depending on their position in the trade network^{15,16} next to their access to food reserves^{17,19}. Previous work²¹ has shown that food crises are not always

correlated with spiking food prices, thereby calling for methods that complement the modelling of food prices^{22,23}.

Even though it has been recognized that shocks co-occur in different parts of the food system¹³, shock propagation models have, so far, often treated each commodity in isolation and neglected that products may be converted into other products along the food production chain. Input–output models provide a well-established formalism to account for the conversion of products into each other^{24,25}. In the context of food systems, this framework was successfully employed to shed light on the use of resources in foreign countries^{26,27}. As a demand-driven model, the input–output formalism is, however, less suitable to assess the propagation of shocks caused by changes in supply rather than demand^{24,28}.

¹Complexity Science Hub Vienna, Vienna, Austria. ²Network Science Institute, Northeastern University, Boston, MA, USA. ³Center for Medical Data Science CeDAS, Medical University of Vienna, Vienna, Austria. ⁴Supply Chain Intelligence Institute Austria, Vienna, Austria. ⁵Institute for Ecological Economics, Vienna University of Economics and Business, Vienna, Austria. ⁶Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland. ⁷Santa Fe Institute, Santa Fe, NM, USA. ✉e-mail: stefan.thurner@meduniwien.ac.at

Here we present a multilayer network model that takes into account both trade between countries and the production dependencies among products. The model parameters are calculated from data on supply and use of individual food products in different countries²⁶. Our model allows us to simulate shocks to the production of individual products and to assess the resulting losses of the same and other products in countries around the globe. We employ our model in three different case studies that are based on the ongoing war in Ukraine, one of the world’s largest producers of maize, wheat and sunflower seeds²⁹. First, we simulate a shock assuming a complete loss of agricultural production in Ukraine and show that the availability of various products in different world regions is severely reduced. Second, we study production shocks across the entire spectrum of food products in Ukraine and the resulting loss of different products. Here we focus on maize and sunflower oil, which make up the largest shares of Ukraine’s food exports. Finally, to demonstrate the versatility of our model to explore other kinds of food shocks, we consider the availability of pork in Germany and identify critical suppliers and production inputs, that is, country and product pairs that would reduce the availability of pork in Germany if they suffer a shock. With this work we therefore establish a tool to assess multiple impacts emerging from shocks on the interconnected trade and production networks.

Results

Understanding trade and production as a multilayer network

Our model describes trade and production of different food products in different countries as an iterated three-step process. These steps are (1) the allocation of products to different purposes, (2) trade with other countries and (3) food conversion and processing activities, that is, production of products using other products as input. Figure 1 represents a simplified version of our model illustrated by means of a multilayer network. For simplicity, it includes only two products, maize and pigs, and three countries, Ukraine, France and Germany. First, country *c* possesses an amount $x_c^i(t)$ of product *i* in iteration *t* and constitutes a node in the multilayer network. In a first step, this amount is allocated in fixed but country- and product-specific proportions to different purposes, namely consumption as food, export, further processing and other uses. This split is represented as a pie chart within each country in Fig. 1.

Second, countries trade with other countries. Country *c* directs a fraction T_{dc}^i of its exports of product *i* towards country *d*. The trade of product *i* corresponds to a single layer of the multilayer network and the fractions T_{dc}^i form a matrix describing this weighted, directed network. The trade links within each layer are depicted as solid arrows in Fig. 1.

In a third step, countries produce new products by converting input products to output products using different types of production processes. The production process of type *k* in country *c* is modelled by a production function f_c^k , which maps the available amount of input products to the amount of output products. These functions constitute a second type of node that acts as an intermediary between replicas of the same country on different product layers. In the example depicted in Fig. 1, the process pig husbandry connects countries in the maize layer to their replica in the pig layer, as maize can be used to feed pigs. The simplified depiction does not show other possible fodder crops included in the model nor does it depict other processes that use maize as an input.

Performing each of the three steps once in every country constitutes a single iteration (model time step) of the algorithm. We define a baseline scenario that consists of ten iterations of the dynamics described above and denote $x_c^i(t)$ the amount of product *i* in country *c* in iteration *t*. We obtain parameters and initial conditions $x_c^i(t=0)$ from trade and production data²⁶ of the year 2013 (Methods). The trade matrices *T* and production functions f_c^k are not re-calibrated to data during the simulation but stay fixed. The variable $x_c^i(t)$ is updated

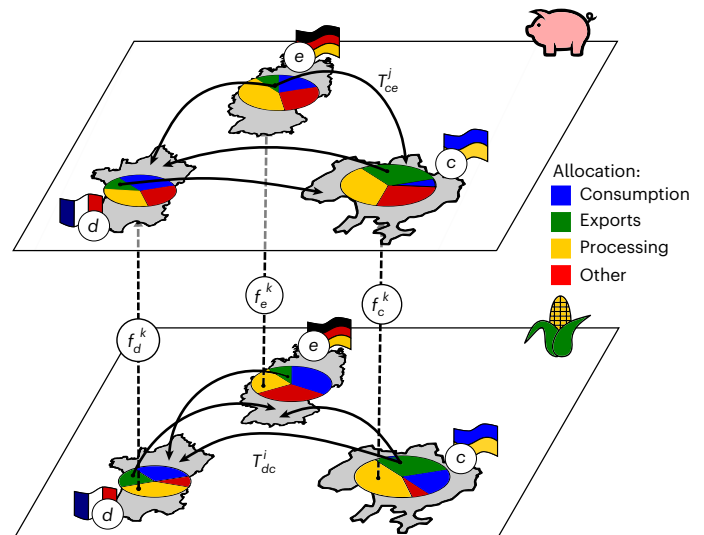


Fig. 1 | Schematic representation of trade and production as a multilayer network for three countries and two products. The allocation of products (maize, lower layer, *i*; pigs, upper layer, *j*) to different purposes is represented as a pie chart within each country (Ukraine, *c*; France, *d*; Germany, *e*). Trade is described by the weighted directed links (solid arrows) within each layer. The entry T_{dc}^i describes the share of country *c*’s exports (green) of product *i* directed towards country *d*. Production processes, modelled as a second type of node, turn products into other products, thereby connecting different layers (dashed arrows). Here the production function f_c^k for the process type *k*, pig husbandry, in country *c* turns maize into pigs. Country *c* is therefore an in neighbour of the process on the maize layer and an out neighbour on the pig layer. Note that production processes can take more than one input and supply more than one output. Credit: icons and country outlines, the Noun Project under a Creative Commons license CC BY 3.0.

according to the production, trade and allocation steps and, therefore, changes each iteration. As we calibrate our model parameters to yearly data, we can think of an iteration as a model year.

Shocks propagate through different channels

We compare the baseline scenario to a shocked scenario. In the shocked scenario, the produced amount of one or more products in a specific country is removed from the model in each time step. We denote the amount of product *i* in country *c* after a shock to product *j* in country *d* as $X_{dc}^{ji}(t)$, where *t* denotes the time step. The relative loss (RL) of product *i* in country *c* after a shock to product *j* in country *d*

$$RL_{dc}^{ji}(t) = \frac{x_c^i(t) - X_{dc}^{ji}(t)}{x_c^i(t)}, \tag{1}$$

describes the relative reduction of the amount of product *i* in country *c* in the shocked scenario with respect to the baseline scenario at iteration *t*. We omit the dependence on iteration *t* when referring to the relative loss in the last iteration t_{end} , $RL_{dc}^{ji} = RL_{dc}^{ji}(t_{end})$.

The quantity RL captures the combined effect of several shock propagation channels. We illustrated the different shock propagation channels with a toy example in Fig. 2. The direct trade relations of a country comprise only one such channel (Fig. 2a). The propagation of shocks on trade networks allows us to capture the effect of trade via third-party countries (Fig. 2b) or an even higher number of intermediaries. Our model accounts for two additional shock propagation channels that result from the possibility to convert products into other products. Losses of product *i* in country *d* can occur if country *d* can no longer import product *j* that it relies on to locally produce product

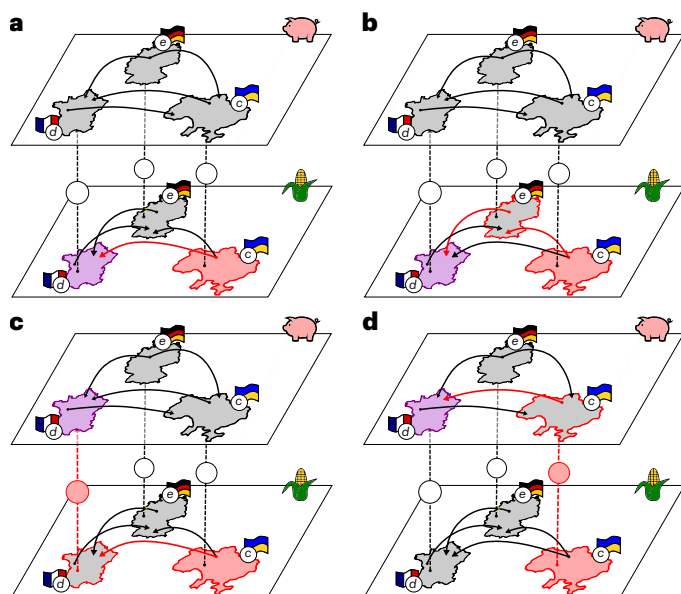


Fig. 2 | A toy example that illustrates different shock propagation channels that can contribute to losses in our model. The shocks to the agricultural production of a good (in this example, maize) in one country (here Ukraine, red) can propagate along different channels (red arrows) that are formed by trade relations (solid red arrows) and production relations (dashed red arrows and red circles) and thereby induce losses in another country (here France, purple). **a**, A direct shock affects direct neighbours in the trade network of the shocked product. **b**, Shock propagation on the trade network leads to indirect shocks that arise through trade via intermediaries, in this example, Germany. **c**, In our model, not only the shocked product but also products that rely on it as an input to be produced are affected. In this case, France lacks a foreign input, Ukrainian maize, to feed pigs. **d**, The shocked product is also not available for production in the shocked country, thereby reducing the exports of those products that rely on it as an input. This opens up another shock propagation channel. In the example, Ukraine produces fewer pigs as it lacks maize as fodder and therefore exports fewer pigs to France. Credit: icons and country outlines, the Noun Project under a Creative Commons license [CC BY 3.0](https://creativecommons.org/licenses/by/3.0/).

i (Fig. 2c). In addition, such losses can occur if a trading partner c lacks an input to produce product i and reduces its exports of product i to country d (Fig. 2d).

Dynamic unfolding of different types of shock transmission

In general, a shock (d, j) to product j in country d can lead to three different types of impact, namely on (1) different products in the same country (local production), (2) the same product in different countries (direct or indirect trade) or (3) different products in different countries. Figure 3 shows the example of shocking product $j = \text{maize}$ in country $d = \text{UKR}$ (Ukraine), the time evolution of the available amount in a baseline case without shock $x_c^i(t)$ and in the shocked scenario $x_c^i(t)$ next to the resulting relative loss $\text{RL}_{dc}^{ji}(t)$. First (different product, same country), this shock can reduce the amount of another product, shown here is $i = \text{poultry}$, in the same country d (Fig. 3a). Second (same product, different country), the shock propagates through trade relations and reduces the availability of the same product, $j = \text{maize}$, in another country, Portugal $c = \text{PRT}$ (Fig. 3b). Third and finally (different product, different country), losses of different products, shown again for $i = \text{poultry}$, can occur in different countries, for example, $c = \text{PRT}$, either through reduced production in c or in other countries (Fig. 3c). Note that the onset of losses is delayed if the shock propagates through multiple production processes and trade (Fig. 3d). In this example, it may take several years until the full production losses after a shock have been realized via all direct and indirect shock transmission channels. Further details of both scenarios are described in Methods.

We characterize the network topology of those layers of the trade network that are most central to our analysis in the Supplementary Information and show that Ukraine occupies a prominent position among the exporters. Here we focus on shocks to the agricultural production of Ukraine, but the effects of shocks to a product of choice in other countries can be explored in our interactive online data visualization³⁰.

The role of Ukraine in the global food system

We examine the losses that occur after a simultaneous shock to the production of all food products \mathcal{F} in Ukraine, UKR . The resulting losses $\text{RL}_{\text{UKR},C}^{\mathcal{F},i}$ of different products i in different world regions C are shown in Fig. 4. The availability of sunflower oil is substantially reduced in several world regions. The two most strongly affected regions are located in Asia, with relative losses of 67.8% arising in southern and 48.8% in eastern Asia. Western Asia ranks fourth with relative losses of 27.1%. The third most-affected region, northern Africa, suffers losses of 48.3%. The effect on Europe is felt most intensely in the north (38.23%) and less so in the south (12.5%), west (10.3%) and east (2.3%). In the latter case, we exclude the losses occurring in Ukraine itself. However, in contrast to Asian regions, Europe and Africa are also affected in their availability of other edible oils, such as rapeseed and mustard seed oil (up to 21.1%) or maize germ oil (up to 23.0%).

The shock in Ukraine also leads to considerable losses of maize in many world regions. Northern and southern Europe are hit strongest with losses of 39.1% and 30.1%, respectively, followed by western Asia with 22.2% and northern Africa with 17.1%. The latter also faces a relative loss of 24.7% of wheat.

Substantial losses also occur for animal products such as poultry meat. Southern Europe suffers losses of 17.2% of poultry and 12.9% of pork. Northern Africa loses 12.4% and 6.6% of the respective products. Losses reach 8.0% (1.3%) of poultry (pig) meat in central and 6.8% (7.0%) in western Asia.

Regions differ considerably by the number of products for which they exhibit a direct or indirect dependence on Ukraine. Southern Europe is strongly affected, with 19 out of 125 products having losses of more than 10%, followed by western Asia and northern Africa, where this is the case for 15 and 11 products, respectively. In contrast, North America and Australia are least affected with only five and seven out of 125 products with a relative loss that exceeds 1%.

In the following, we assess the role of production versus trade in the shock propagation. We compare the relative loss of different products i after two types of shock. On the one hand, we shock a fixed product j in Ukraine and compute the relative loss, $\text{RL}_{\text{UKR},C}^{ji}$, of other products i in different world regions C . On the other hand, we shock the same products i in Ukraine and monitor the losses for i in other regions, that is, we compute $\text{RL}_{\text{UKR},C}^{ii}$. The former quantifies the losses that arise on a different layer and therefore involve the conversion of products into other products, while the latter quantifies the effect within one layer, that is, international trade. Whereas a shocked country can still re-export products that it imported, we found that the share of re-exports is low in the case of Ukraine and the within-layer effect constitutes a good measure for trade-related losses, (Supplementary Information).

Downstream impacts of a shock to Ukrainian maize production

In Figure 5a, these production- and trade-related contributions to the relative losses are shown for a shock to Ukrainian maize production. Colours reflect the size of losses, and each cell describes the losses of an affected product i in an affected region C . Cells are split into two parts. The left half captures the production-related losses after a shock to Ukrainian maize, $\text{RL}_{\text{UKR},C}^{\text{maize},i}$, and therefore quantifies an effect across layers. The right half, on the other hand, captures the losses after a trade-related shock in Ukraine to product i itself, $\text{RL}_{\text{UKR},C}^{ii}$, and therefore quantifies the importance of Ukraine within one layer.

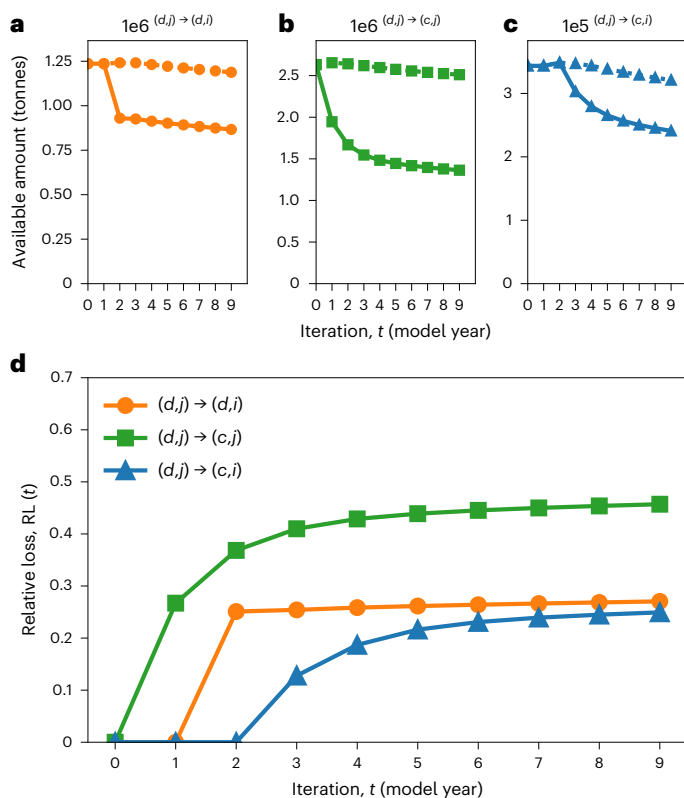


Fig. 3 | Time evolution of the available amount in a baseline case and after a shock next to the resulting relative loss. **a–c**, Available amount (**a–c**) and relative losses (**d**) as model time passes for three different types of shock propagation channel. In each panel we consider a shock to a product, $i = \text{maize}$, in a country, Ukraine $d = \text{UKR}$, and the ensuing reduction of the available amount in the shocked scenario (solid line) with respect to the baseline scenario (dotted line). We show results for a different product, $i = \text{poultry}$, in the same country d (**a**), for the same product j in another country, Portugal $c = \text{PRT}$ (**b**), and for a different product i in a different country c (**c**).

For the product maize itself, both sides are equal by definition. The strongest effects of maize in Ukraine on maize in other countries occur in northern Europe with losses of 39.1%, but southern Europe (30.1%), western Asia (22.2%) and northern Africa (17.1%) are affected as well. Note that these losses incorporate not only the lack of maize that is directly imported from Ukraine but also reduced domestic production due to lack of seeds and the trade with third-party countries that might also rely on imports from Ukraine.

In addition, the upper part of Fig. 5 shows that the shock to Ukrainian maize influences the availability of pig and poultry meat in Europe, northern Africa and western Asia. For poultry meat, the relative loss after a shock to maize in Ukraine amounts to 15.4% in southern Europe, 4.9% in northern Africa and 3.9% in western Asia. This contrasts the losses after a shock to the Ukrainian poultry meat production, which stay below 1% in these world regions. This indicates that the losses in these world regions arise from a lack of fodder maize in the domestic poultry meat production and not from a trade of poultry meat with Ukraine. A similar pattern can be observed in the supply of other products that rely on maize as an input to production.

The availability of sweeteners in central Asia is an exception. Here the effect within one layer, with losses of 28.3%, is larger than the effect across layers, with a loss of 11.1%, after a shock to the Ukrainian maize production. Similarly, the relative loss of alcoholic beverages in central Asia after a shock to this product in Ukraine amounts to 1.5% and exceeds the losses of 0.7% that occur after a shock of Ukrainian maize

production. This situation arises as both products can be made from a variety of input products other than maize.

Ukraine is a critical supplier of sunflower oil

Figure 5b shows results for a shock to the sunflower seed production of Ukraine. In contrast to the maize shock in Fig. 5a, the losses induced across layers (left half) and within the same layer (right half) are of similar size. In southern and eastern Asia, relative losses of 67.7% and 48.7% of sunflower oil are observed for a shock to the Ukrainian sunflower seed production. A shock to Ukrainian sunflower oil leads to equal losses in these world regions. Losses of similar size occur in northern Africa, which loses 48.2% due to a shock to sunflower seeds and 48.1% after a shock to sunflower oil, and northern Europe with losses of 38.2% and 38.1%, respectively. The difference between the two types of shock is largest in western Asia where losses of 27.0% of sunflower oil arise after a shock to Ukrainian sunflower seeds and 24.8% after a shock to Ukrainian sunflower oil. As a shock to Ukrainian sunflower seeds also causes losses of 5.2% of sunflower seeds in this region, the additional losses are probably due to a reduced local production of oil as a result of the reduced availability of sunflower seeds. Most world regions also suffer losses of sunflower cake, a residue from oil seed crushing that can be used as fodder. The largest losses occur in western Africa 42.9%, northern Europe 39.1% and western Europe 28.1% for a shock to Ukrainian sunflower seeds. For a shock to Ukrainian sunflower cake itself, losses are slightly lower or equal, amounting to 42.4%, 39.1% and 28.1% in the respective world regions. The relative losses of sunflower seeds in all world regions are much weaker than the losses of sunflower oil. Our multilayer modelling framework can readily be applied to other types of shock, which we demonstrate in the Supplementary Information within a case study to identify dependencies of German pork production.

Discussion

We propose a multilayer network model that accounts for production dependencies among 125 food and agricultural products, allowing us to assess the losses of food products around the globe after a localized shock. The model takes into account trade dependencies and the conversion of products into other products along the global supply chain. We use data on production and trade of food and agricultural products to determine the parameters of the model. We introduce the relative loss, RL, that describes the multidimensional dependencies of the availability of various food products in each country with respect to shocks to food products in any other country in an easily interpretable way.

First, we show that a complete shock to Ukrainian production leads to stark losses to grains and dietary oils in parts of Europe, western Asia and northern Africa. It seems plausible to assume that high-income countries will be able to mitigate the losses by tapping into reserves or switching suppliers in spite of possible higher costs, while middle- and low-income countries are probably unable to mitigate the losses. In northern Africa and western Asia, food security was already critical before the onset of the war due to factors that vary on a country-by-country basis but include the aftermath of supply-chain disruption due to the COVID-19 pandemic, extreme weather events and local conflict. Our results corroborate the increased risk of a food crisis in these regions^{31,32}. Large losses in grain supply are likely to have direct adverse effects on food security given the large shares of grains in the diets of countries in these regions, for example, wheat makes up about 35.3% of the caloric intake in Egypt and 39.6% in Syria³³ and is also an important protein source³⁴. Even in countries in which food security is not directly threatened, supply disruptions can make healthy and nutritious food less affordable, thereby forcing low-income households to switch to less nutritious food options³². Overall, these findings highlight the importance of Ukraine as a critical supplier of agricultural products and serve as an example for the fragility of global supply chains with respect to the failure of key producers due to geopolitical instability.

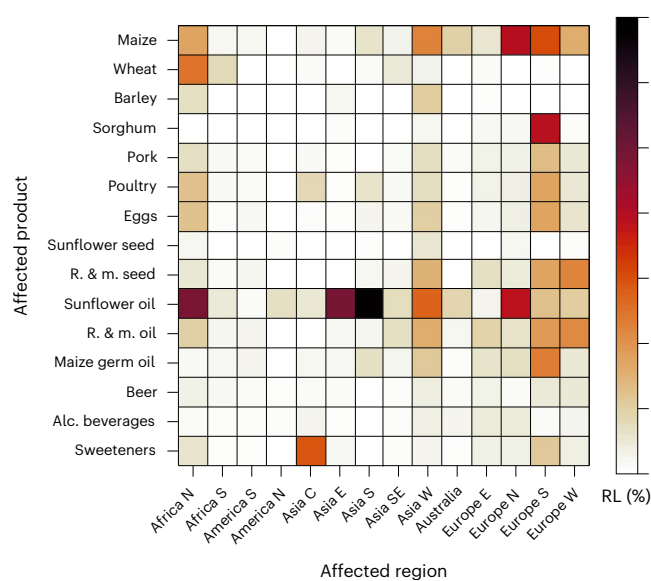


Fig. 4 | A simultaneous shock to the production of all food products in Ukraine affects different world regions and products. The relative loss of a given affected product in an affected region is colour-coded. The largest losses occur for sunflower oil in southern Asia, amounting to 67.8% of the total production without shock. Parts of Europe, North Africa and western Asia suffer losses in a diverse range of products including grains, edible oils, animal and luxury products, while the Americas and Australia are affected to a somewhat weaker degree. Sunflower oil stands out as the product most severely affected, but substantial losses also occur for other edible oils and grains. Rapeseed and mustard are abbreviated as 'R. & m.', alcoholic beverages as 'Alc. beverages' and central as 'C'.

Second, we investigate the effects of shocks to single products in Ukraine on several other products in different world regions. We compare the effects of a shock to an important input product on more processed products, that is, shock propagation across layers, to the effects of shocks to the processed products themselves, that is, shock propagation within the same layer. We find that the production loss of pork and poultry in southern Europe, western Asia and northern Africa relies heavily on the imports of fodder maize from Ukraine but that the role of direct meat imports from Ukraine is small. This means the shock propagation channel shown in Fig. 2c, where countries import a shock along with inputs they require for their domestic food production, contributes considerably to the losses.

In contrast, shocks to sunflower seeds, the input product, and to sunflower oil, the processed product, lead to similar losses abroad. Shock propagation is probably dominated by the channel displayed in Fig. 2d, that is, losses in inputs to domestic production processes that propagate to other countries via exports of the processed product. As we measure relative and not absolute loss, we can identify a substantial reduction of the availability of sunflower oil in South and East Asia. While these are not the largest importers of Ukrainian sunflower oil in absolute terms, a large share of their sunflower oil imports stems from Ukraine. This shows how non-diversified supply relations can lead to large relative losses in case of a shock. Both cases highlight the importance of integrated trade and production processes in the assessment of losses. Shocks to input products in a given country can propagate to other product layers, either through the production processes in the same country or after trade in other countries, thereby causing losses in downstream products. This is especially apparent in the case of maize, as the crop does not only substantially contribute to the daily diet in many countries, both in terms of caloric intake and protein supply, but also serves many other use cases. The latter includes, on the

one hand, feed for livestock and, on the other hand, the production of bioenergy³⁵. Balancing these conflicting use cases and associated (economic) interests poses a challenge for the relevant stakeholders. Our analysis raises attention for this type of interdependence and calls to address the associated challenges. From a methodological perspective, we emphasize that losses downstream in the supply chain can be obscured in a risk analysis based on trade data alone. This underscores the need to routinely extend risk analysis along more than one product dimension in global production networks.

These examples illustrate the wide-ranging consequences of the ongoing war in Ukraine and how our model can be used to assess supply disruptions that can reduce the availability of nutritious food. Additional mechanisms, such as price increases, can shift the burden further upon vulnerable populations, thereby exacerbating existing food insecurity and nutritional challenges³⁶. Our study shows how a spatially confined shock does not only affect the local population, but can lead to global supply disruptions. It also shows that these adverse effects extend along the entire supply chain, from the cultivation of crops to the production of food and animal feed, to the livestock sector, all the way to the consumer. Managing the risk along the food supply chain resulting from the conflict in Ukraine requires a multifaceted perspective that takes both direct and indirect effects into account. Our results enhance supply-chain visibility and transparency. This can help identify potential risks and disruptions in the food system and develop contingency plans that enable food supply-chain stakeholders to prepare for potential disruptions and mitigate their impact. For countries that heavily depend on Ukrainian imports – either directly or indirectly – this could, for example, mean diversifying their supply of imports. Viewing the food supply chain as a network with interdependent layers can inform policies that rely on local interventions and resulting ripple effects to counter existing crises. For example, it suggests that positive effects of providing seed material and assuring access to means of production can extend beyond the directly supported crop producers. It also suggests that care has to be taken when allocating resources to different use cases and that it might be necessary to adapt allocation strategies during a crisis, for example, by using certain crops directly as food rather than as input for further production processes. In all cases, countries should strive to minimize food waste. Re-examining previous work^{18,37} showing that cascading export restrictions can exacerbate shortages in the light of inter-product dependencies makes clear that export bans on single products could potentially lead to unintended side effects on other products, worsening the situation even further.

While existing studies of the international food system have created valuable insights, our work addresses various open challenges in the field: previous shock propagation frameworks were limited to a few products^{9,18,19,38} or aggregated them in terms of calories^{17,20}, monetary units³⁷ or virtual water^{15,39}. Here we extended a shock propagation to 125 food and agricultural products. We also took into account the production dependencies among these products, while previous work considered products in isolation. This includes studies that simulate the international propagation of food supply shocks^{9,17–20}, analyse historical shocks to production^{12,21} and descriptions⁶ and predictions⁵ of the food trade network topology. Finally, the explicit representation of production processes opens up the possibility to customize production functions if sufficient data on the production process of individual products were available. This sets our work apart from existing shock propagation frameworks that work directly with input–output tables²⁰.

Nonetheless, our study faces several limitations: the proposed model provides a simple, mechanistic picture of the dynamics of food trade and production. We focus on the conversion of products into each other and do not consider impacts of stocks and changing resource allocation based on availability. Furthermore, we simulate dynamics that take place on a static multilayer network. As a result, we do not capture the dynamical restructuring of supply relations that are likely to occur after a shock. This concerns, on the one hand, trade relations

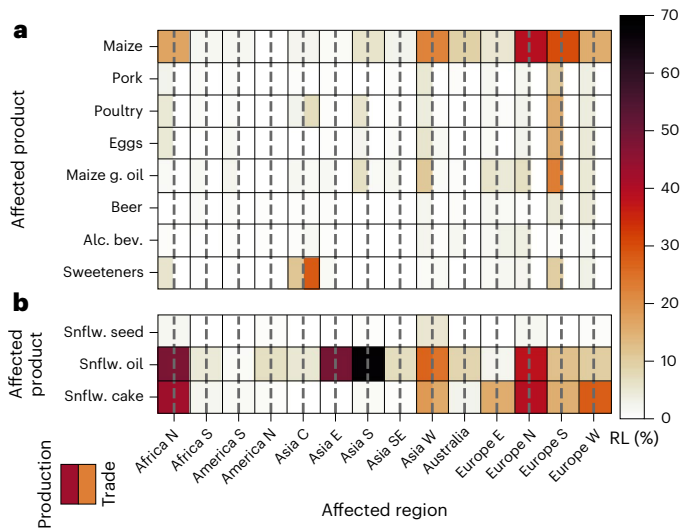


Fig. 5 | Comparison of losses within one layer (trade) and across layers (production). Each cell displays the loss of an affected product *i* in a specific region after a shock in Ukraine and is split into two halves by a grey dashed line. The left half represents contributions to the losses that stem from a shock to products other than product *i*, which can roughly be identified with contributions from production processes across different network layers. The right half shows contributions from a shock to product *i* itself that are mostly mediated via relationships in a single trade layer. **a.** Losses after a shock to Ukrainian maize production, for which we observe production-related losses in several other food products. **b.** Losses after a shock to Ukrainian sunflower seeds. In this case, losses via production and trade, respectively, are of similar size. Maize germ oil is abbreviated ‘Maize g. oil’, alcoholic beverages as ‘Alc. bev.’, sunflower as ‘Snflw’ and central as ‘C’.

in which a failing exporter may be replaced by a competitor on the market and, on the other hand, production relations in which production recipes can be adapted to some extent based on the available products. These issues are tightly connected to prices and markets, which are not included in our mechanistic model. The above effects have been shown to redistribute the burden of the losses^{16,17} as countries that have stocks available or are wealthy enough to buy resources at higher prices can buffer shocks, while countries that lack these capabilities might be affected more strongly. Our model represents a worst-case scenario of a complete and sustained production loss and is likely to overestimate real losses. Nevertheless, our results might inform crisis response by providing estimates for the losses incurred in individual countries unless they make substitution efforts or consider other mitigation measures.

We restrict ourselves to the case of linear production functions. The incorporation and comparison of other production functions opens up possibilities for future research. Work on shocks in firm-level supply-chain networks suggests that nonlinear production functions of the Leontief type can lead to larger losses compared to situations with linear production functions⁴⁰. We expect this effect to influence our results, particularly in cases where a production recipe includes a comparably small but essential amount of an input, for example, hops for beer production.

Furthermore, the data have limits in terms of spatial resolution and granularity and scope of products. On the one hand, data on the subnational level would allow us a more realistic assessment of losses. This is especially true for shocks such as natural disasters or extreme weather events that are spatially localized but do not stop at national borders. On the other hand, finer resolution on the product level would enable us to better trace shocks through the process of production. The product wheat, for example, also encompasses certain wheat products

such as bread and pasta. Extending the model to non-food input products, such as fertilizers^{41,42} or machinery, is necessary to create a more complete picture of a country’s dependencies.

We have chosen to base our model on shocks to products to reflect losses that occur if the product itself or necessary means of production are destroyed, for example, by armed conflict or natural disasters. However, other scenarios such as blockage of exports either because of an export ban¹⁸ or physical blockade of infrastructure, are conceivable and could be incorporated into the model. In context of the war in Ukraine, both scenarios contribute. On the one hand, a naval blockade makes it impossible to export maize and wheat, and on the other hand, the agricultural production itself is on halt as farmers serve as soldiers, fields are mined and infrastructure is destroyed^{43,44}.

While food security extends far beyond the trade- and production-centred perspective adopted herein and incorporates social, cultural and ecological aspects^{7,11,14}, production and trade are essential components to secure the basic availability of food. While we focused here on the ongoing war in Ukraine, armed conflict is only one among many possible causes of shocks to the global food system, as in an age of climate change, crop failures due to droughts, other extreme weather events or food pests become increasingly likely. Tools from complexity and network science, as those presented herein, enable us to uncover direct and indirect dependencies along the global supply chain⁴⁵ in these and other scenarios. Raising awareness for the multidimensional systemic risk incorporated in the global trade and production of food can help to design more resilient supply chains.

Methods

Food production and trade as an iterative three-step process

The model consists of 192 countries that trade and produce 125 food and agricultural products. The set of countries is denoted *c* and the set of products *F*. Production is modelled by 118 types of production process, which form a set *P*. This corresponds to the countries and territories, products and production processes of the food and agriculture biomass input–output (FABIO) model²⁶. The mapping of countries and territories to world regions can be found in the Supplementary Information. A python implementation of the model together with input data in a suitable format is publicly available⁴⁶. A country *c* possesses a total amount $x_c^i(t)$ of a product *i* at iteration *t*. This amount is split in fixed but country- and product-specific fractions $\eta_{c,i}^k$ to serve different purposes *k* (here and in the following, index variables used as superscripts denote indexes, not exponents). These purposes are exports (exp), $\eta_{c,i}^{exp}$, input to production (prod), $\eta_{c,i}^{prod}$, consumption as food, $\eta_{c,i}^{food}$, and other uses, $\eta_{c,i}^{else}$, including waste, non-food consumption and stockpiling. The amount $x_c^i(t)$ changes as countries repeatedly undergo the three-step process of production, trade and allocation to different purposes.

In the first step, countries rely on different types of production process to create and to convert products into each other. For each type of process *k* in each country *c*, there exists a function $f_{c,i}^k(p_c(t-1))$ that maps the available amounts of inputs $p_c(t-1)$ from the previous time step to the produced amount of output product *i* supplied by this process. Here $p_c(t-1)$ denotes a vector with components $p_c^j(t-1) = \eta_{c,j}^{prod} x_c^j(t-1)$. As different processes can supply the same output product, the total amount $o_c^i(t)$, of product *i* produced in country *c* at iteration *t* is

$$o_c^i(t) = \sum_{k \in \mathcal{P}} f_{c,i}^k(p_c(t-1)). \tag{2}$$

An example of a product that is supplied by multiple processes is animal fats or animal hides, which accrue in the slaughter of different types of animal.

Moreover, it is possible that different types of process use the same input product. Therefore, it is necessary to split the amount $p_c^j(t-1)$

of product j that is available for production in a country c among the processes that use it. The fraction assigned to a particular process k is denoted $v_{c,j}^k$ and depends on the country c , the product i and the process type k . This case occurs, for example, in the farming of poultry and pigs, which can both be fed with maize. The assumption that the input products are completely substitutable as long as they are from the set of valid input products $J_{c,k}$ to the production process k in country c motivates

$$f_{c,i}^k(p_c(t-1)) = \alpha_{c,i}^k \sum_{j \in J_{c,k}} v_{c,j}^k p_c^j(t-1) + \beta_{c,i}^k, \quad (3)$$

as a mathematical form for the amount of a product i produced by a process k in a country c . Here $\alpha_{c,i}^k$ is the amount of output product i that can be produced by process k in country c for a given amount of input, and $\beta_{c,i}^k$ is the amount of product i produced in absence of any input. In the present initiation of the model, either $\beta_{c,i}^k$ or $\alpha_{c,i}^k$ is non-zero, but not both. The production of apples is an example for a process with non-zero $\beta_{c,i}^k$. In other cases, non-zero values of $\beta_{c,i}^k$ occur because countries report outputs of a process even though it is reasonable to assume that the process would rely on inputs.

In a second step of iteration t , each country d trades the amount $e_d^i(t-1)$ of product i that it reserved for this purpose in the previous iteration, $t-1$. The trade of each product i is governed by a weighted, directed network described by a matrix T^i and countries as nodes. An entry, T_{cd}^i , of this matrix indicates the share of country d 's exports that country c receives. This allows us to write the imports, $h_c^i(t)$, of product i of country c in time step t as

$$h_c^i(t) = \sum_{d \in \mathcal{E}} T_{cd}^i e_d^i(t-1). \quad (4)$$

The trade relations between countries and the production dependencies among products can thus be represented as a bipartite multilayer network. The trade network for each product forms a single layer with countries as nodes, and the links indicate trade relations. The replica nodes, representing the same country on different layers, are connected by directed interlayer links via nodes of a second type, which represent different production processes. A country node in a layer representing the trade of a product is in neighbour of a specific process in that country if this product is an input to the production process, and it is an out neighbour if the product is an output of the production process.

In the third step, allocation, each country c assigns fractions of the total available amount of product i , $x_c^i(t) = o_c^i(t) + h_c^i(t)$, obtained either from domestic production or imports from other countries to different purposes according to

$$p_c^i(t) = \eta_{c,i}^{\text{prod}} x_c^i(t) \quad (5)$$

$$e_c^i(t) = \eta_{c,i}^{\text{exp}} x_c^i(t) \quad (6)$$

$$k_c^i(t) = \eta_{c,i}^{\text{food}} x_c^i(t) \quad (7)$$

$$r_c^i(t) = \eta_{c,i}^{\text{else}} x_c^i(t), \quad (8)$$

where $k_c^i(t)$ denotes the amount of product i allocated by country c to consumption as food and $r_c^i(t)$ the amount of product i that country c allocates to all other purposes, such as waste, non-food consumption and stockpiling. Thereafter the accounting variable $x_c^i(t)$ is reset and the next time step begins with the first sub-step, production. We calibrate the parameters and initial conditions, that is, available amount at time step $t=0$ of our model to trade and production data of the year

$\tau=2013$, as described below. Note, that while the topology of the trade network, the fractions of goods assigned to different purposes and the production functions stay fixed during simulation, the total available amount of each product—and as a consequence also the amount assigned to each purpose—changes with each iteration t . This gives rise to dynamics on a static network. An overview over parameters and variables, how they are obtained and whether they are static or time-dependent can be found in the Supplementary Information.

The relative loss captures the effects of a shock

To determine the effects that a shock to the production of certain products in certain countries has on the availability of all other products in all other countries, we compare a baseline scenario to a shocked scenario. The baseline scenario consists of iterating the dynamics described above for $t_{\text{end}}=10$ time steps. In the shocked scenario, a fraction ϕ of the production output $o_d^j(t)$ of the shocked product j in the shocked country d is destroyed after the production step. This means only an amount

$$(1-\phi)o_d^j(t) \quad (9)$$

is available after production at all times, $t \in \{0, \dots, t_{\text{end}}\}$. Here we investigate a worst-case scenario in which the complete production is lost, that is, $\phi=1$, and this production failure persists over all iterations. A shock to more than one product is realized by applying equation (9) to all products j from a set of shocked products. The same is true for shocks to more than one country.

The relative loss RL_{dc}^i of product i in country c in response to a shock to the production of product j in country d is a measure for the severity of the adverse effects on a country and defined as the relative reduction in total available amount in the shocked country with respect to the baseline scenario

$$RL_{dc}^i(t) = \frac{x_c^i(t) - X_{dc}^{ji}(t)}{x_c^i(t)}, \quad (10)$$

with $X_{dc}^{ji}(t)$ denoting the total amount of product i available in a country c at time step t after a shock to product j in country d and $x_c^i(t)$ denoting the total amount of product i available in country c at time t in the baseline scenario. We drop the time dependence when referring to the relative loss in the last time step $RL_{dc}^i = RL_{dc}^i(t_{\text{end}})$. To assess the effect of a shock on a whole region \mathcal{C} that consists of several countries, we aggregate the available amount of a product i on the regional level

$$RL_{dc}^i = \frac{\sum_{c \in \mathcal{C}} x_c^i(t_{\text{end}}) - \sum_{c \in \mathcal{C}} X_{dc}^{ji}(t_{\text{end}})}{\sum_{c \in \mathcal{C}} x_c^i(t_{\text{end}})}. \quad (11)$$

Supply and use tables of the FABIO model

The free parameters of the model are determined from the supply and use tables of the FABIO model²⁶ for the year 2013. The FABIO model is a multiregional input–output model in physical units. The entry $S_{(c,k),(d,i)}$ of the supply table S describes the amount of product i that production process k generates in country d . Processes supply only to the country in which they are based and therefore the supply table is country-block diagonal, that is

$$c \neq d \Rightarrow S_{(c,k),(d,i)} = 0 \quad \forall i \in \mathcal{F} \wedge k \in \mathcal{P}. \quad (12)$$

The entry $U_{(d,i),(c,k)}$ of the use table U gives the amount of product i originating from country d that process k in country c uses. Countries can use products from different countries and therefore the use table U has no special block structure.

The demand table entry $Y_{(d,i),(c,i)}$ specifies the amount of product i from country d that country c uses to satisfy the demand for the

purpose l . These purposes are labelled food, losses, stock addition, other, unspecified and balancing. They are summarized in the set \mathcal{V} . We denote the positive part of the demand Y as Y^+ and the negative part as Y^- . The latter can only be non-zero if $l \in \{\text{balancing, stock addition}\}$. The sets of products, countries and processes are adopted directly from the FABIO model, as described in ref. 26.

Trade networks

The entry T_{cd}^i of the matrix T describes the share of exports of product i from country d that are directed towards country c . It is determined as the amount of a product i originating from country d used either by any production process k in country c or to satisfy any demand purpose l in country c relative to the amount of product i from country d that is used by any production process k or any demand purpose l in any country other than d itself, that is

$$T_{cd}^i = \frac{\sum_{k \in \mathcal{P}} U_{(d,i),(c,k)} + \sum_{l \in \mathcal{V}} Y_{(d,i),(c,l)}^+}{\sum_{k \in \mathcal{P}, c \neq d} U_{(d,i),(c,k)} + \sum_{c \neq d, l \in \mathcal{V}} Y_{(d,i),(c,l)}^+} \quad (13)$$

for $c \neq d$ and $T_{cd}^i = 0$ if $c = d$. By definition, the entries satisfy $T_{cd}^i \in [0, 1]$ and the out strength of a country is always

$$\sum_{c \neq d} T_{cd}^i = 1 \quad \forall d \in \mathcal{C} \wedge i \in \mathcal{F}. \quad (14)$$

Allocation to use cases

To avoid negative demands Y^- , we introduce a balancing term for each country c and product i as the difference between the supply of the product i by any local process and the sum of the domestic or foreign use of the product by any process and the positive part of the domestic or foreign demand for the product for any purpose,

$$B_{(c,i)} = \sum_{p \in \mathcal{P}} S_{(c,p),(c,i)} - \sum_{d \in \mathcal{C}, p \in \mathcal{P}} U_{(c,i),(d,p)} - \sum_{d \in \mathcal{C}, k \in \mathcal{V}} Y_{(c,i),(d,k)}^+ \quad (15)$$

The positive part of the balancing B is denoted B^+ and its negative part as B^- . With this balanced demand, it is possible to determine the fractions $\eta_{c,i}^k$ that are used in the allocation step. The share of products used as input to production $\eta_{c,i}^{\text{prod}}$ is the amount of product i originating from any foreign country and used in any local process in country c divided by the sum of this amount and the amount of product i originating from any country and used to satisfy any type of demand in country c and the balancing term for product i in country c

$$\eta_{c,i}^{\text{prod}} = \frac{\sum_{k \in \mathcal{P}, d \in \mathcal{C}} U_{(d,i),(c,k)}}{\sum_{k \in \mathcal{P}, d \in \mathcal{C}} U_{(d,i),(c,k)} + \sum_{d \in \mathcal{C}, l \in \mathcal{V}} Y_{(d,i),(c,l)}^+ + B_{(c,i)}^+} \quad (16)$$

The fraction $\eta_{c,i}^{\text{food}}$ of product i used to satisfy the demand for food in a country c is obtained by dividing the amount of product i originating in any country and used to satisfy food demand in country c by the same denominator

$$\eta_{c,i}^{\text{food}} = \frac{\sum_{d \in \mathcal{C}} Y_{(d,i),(c,\text{food})}^+}{\sum_{k \in \mathcal{P}, d \in \mathcal{C}} U_{(d,i),(c,k)} + \sum_{d \in \mathcal{C}, l \in \mathcal{V}} Y_{(d,i),(c,l)}^+ + B_{(c,i)}^+} \quad (17)$$

The fraction $\eta_{c,i}^{\text{else}}$ that is used for any non-food purpose is obtained by summing the demand in the numerator over all non-food demand purposes including the balancing, that is

$$\eta_{c,i}^{\text{else}} = \frac{\sum_{d \in \mathcal{C}, l \in \mathcal{V} \setminus \{\text{food}\}} Y_{(d,i),(c,l)}^+ + B_{c,i}^+}{\sum_{k \in \mathcal{P}, d \in \mathcal{C}} U_{(d,i),(c,k)} + \sum_{d \in \mathcal{C}, l \in \mathcal{V}} Y_{(d,i),(c,l)}^+ + B_{(c,i)}^+} \quad (18)$$

Finally the share of product i that country c reserves for exports in the allocation step is calculated by dividing the amount of a product i originating from a country c that is used either by any production

process in any foreign country or to satisfy any type of demand in any foreign country

$$\eta_{c,i}^{\text{exp}} = \frac{\sum_{k \in \mathcal{P}, d \neq c} U_{(c,i),(d,k)} + \sum_{d \neq c, l \in \mathcal{V}} Y_{(c,i),(d,l)}^+}{\sum_{k \in \mathcal{P}, d \in \mathcal{C}} U_{(c,i),(d,k)} + \sum_{d \in \mathcal{C}, l \in \mathcal{V}} Y_{(c,i),(d,l)}^+ + B_{(c,i)}^+} \quad (19)$$

By definition, these fractions cover all possible use cases and thus

$$\eta_{c,i}^{\text{prod}} + \eta_{c,i}^{\text{food}} + \eta_{c,i}^{\text{exp}} + \eta_{c,i}^{\text{else}} = 1 \quad \forall c \in \mathcal{C} \wedge i \in \mathcal{F}. \quad (20)$$

Properties of production processes

During the production step, the amount of a product i available for production in a country c needs to be split among the different processes that use it as an input. The corresponding fraction $v_{c,i}^k$ of this amount that a process k obtains is calculated as the quotient of the amount of product i originating from any country used by process k in country c by the amount of product i originating from any country used by any process in country c

$$v_{c,i}^k = \frac{\sum_{d \in \mathcal{C}} U_{(d,i),(c,k)}}{\sum_{d \in \mathcal{C}, k \in \mathcal{P}} U_{(d,i),(c,k)}} \quad (21)$$

As a result of this definition, no share of input products is left unused and the fractions satisfy

$$\sum_{k \in \mathcal{P}} v_{c,i}^k = 1 \quad \forall c \in \mathcal{C} \wedge i \in \mathcal{F}. \quad (22)$$

The production process of type k based in a country c is defined by coefficients $\alpha_{c,i}^k$ that describe how much of output product i is produced per amount of available input. For each process type k in country c , the set of output products $\mathcal{O}_{c,k}$ comprises those products that the process supplies

$$\mathcal{O}_{c,k} = \{i | S_{(c,k),(c,i)} > 0 \text{ for } k \in \mathcal{P} \wedge i \in \mathcal{F}\}. \quad (23)$$

The set of input products $\mathcal{J}_{c,k}$ to process type k in country c consists of those products of which a non-zero amount is used by the process

$$\mathcal{J}_{c,k} = \{i | U_{(d,i),(c,k)} > 0 \text{ for } d \in \mathcal{C} \wedge j \in \mathcal{F}\}. \quad (24)$$

The same process type can therefore supply different products and rely on different inputs depending on the country. For example, the composition of the fodder that animals receive in different countries might vary. If the process relies on inputs $\mathcal{J}_{c,k} \neq \emptyset$, then $\beta_{c,i}^k = 0$ and

$$\alpha_{c,i}^k = \frac{S_{(c,k),(c,i)}}{\sum_{d \in \mathcal{C}, j \in \mathcal{J}_{c,k}} U_{(d,j),(c,k)}} \quad \text{if } i \in \mathcal{O}_{c,k}, \quad (25)$$

but $\alpha_{c,i}^k = 0$ if $i \notin \mathcal{O}_{c,k}$. If the process does not rely on inputs $\mathcal{J}_{c,k} = \emptyset$, then $\alpha_{c,i}^k = 0$ and $\beta_{c,i}^k = S_{(c,k),(c,i)}$ for $i \in \mathcal{O}_{c,k}$ and $\beta_{c,i}^k = 0$ for $i \notin \mathcal{O}_{c,k}$.

At time $t = 0$, each country c starts with a total available amount $x_c^i(0)$ of product i that equals the positive domestic and foreign demand and the amount used by any foreign or domestic production process

$$x_c^i(0) = \sum_{d \in \mathcal{C}, k \in \mathcal{P}} U_{(c,i),(d,k)} + \sum_{d \in \mathcal{C}, l \in \mathcal{V}} Y_{(c,i),(d,l)}^+ \quad (26)$$

This amount determines the initial values for production input $p_c^i(0)$ and exports $e_c^i(0)$. Negative demand and balancing terms are taken into account by adding the amount

$$x_c^i = - \sum_{d \in \mathcal{C}} Y_{(d,i),(c,\text{stock_addition})}^- - B_{(c,i)}^- \quad (27)$$

to the output $o_c^i(0)$ in the first iteration $t = 0$.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data used in this study as input for simulations are available on GitHub at <https://github.com/L-MoNi/shock-propagation-food-supply>.

Code availability

Python was used to perform the simulations and data analysis. Simulation and analysis code for this study is available in a repository at <https://github.com/L-MoNi/shock-propagation-food-supply>.

References

- Ercsey-Ravasz, M., Toroczkai, Z., Lakner, Z. & Baranyi, J. Complexity of the international agro-food trade network and its impact on food safety. *PLoS ONE* **7**, 37810 (2012).
- D'Odorico, P., Carr, J. A., Laio, F., Ridolfi, L. & Vandoni, S. Feeding humanity through global food trade. *Earth's Future* **2**, 458–469 (2014).
- MacDonald, G. K. et al. Rethinking agricultural trade relationships in an era of globalization. *BioScience* **65**, 275–289 (2015).
- Dupas, M.-C., Halloy, J. & Chatzimpiros, P. Time dynamics and invariant subnetwork structures in the world cereals trade network. *PLoS ONE* **14**, 0216318 (2019).
- Fair, K. R., Bauch, C. T. & Anand, M. Dynamics of the global wheat trade network and resilience to shocks. *Sci. Rep.* **7**, 7177 (2017).
- Berfin Karakoc, D. & Konar, M. A complex network framework for the efficiency and resilience trade-off in global food trade. *Environ. Res. Lett.* <https://doi.org/10.1088/1748-9326/ac1a9b> (2021).
- Bernard de Raymond, A. et al. Systemic risk and food security. Emerging trends and future avenues for research. *Glob. Food Secur.* **29**, 100547 (2021).
- Puma, M. J., Bose, S., Chon, S. Y. & Cook, B. I. Assessing the evolving fragility of the global food system. *Environ. Res. Lett.* **10**, 024007 (2015).
- d'Amour, C. B., Wenz, L., Kalkuhl, M., Steckel, J. C. & Creutzig, F. Teleconnected food supply shocks. *Environ. Res. Lett.* **11**, 035007 (2016).
- Kummu, M. et al. Interplay of trade and food system resilience: gains on supply diversity over time at the cost of trade independency. *Glob. Food Secur.* **24**, 100360 (2020).
- Gaupp, F. Extreme events in a globalized food system. *One Earth* **2**, 518–521 (2020).
- Gephart, J. A., Deutsch, L., Pace, M. L., Troell, M. & Seekell, D. A. Shocks to fish production: identification, trends, and consequences. *Glob. Environ. Change* **42**, 24–32 (2017).
- Cottrell, R. S. et al. Food production shocks across land and sea. *Nat. Sustainability* **2**, 130–137 (2019).
- Reichstein, M., Riede, F. & Frank, D. More floods, fires and cyclones—plan for domino effects on sustainability goals. *Nature* **592**, 347–349 (2021).
- Tamea, S., Laio, F. & Ridolfi, L. Global effects of local food-production crises: a virtual water perspective. *Sci. Rep.* **6**, 18803 (2016).
- Gephart, J. A., Rovenskaya, E., Dieckmann, U., Pace, M. L. & Brännström, Å. Vulnerability to shocks in the global seafood trade network. *Environ. Res. Lett.* **11**, 035008 (2016).
- Marchand, P. et al. Reserves and trade jointly determine exposure to food supply shocks. *Environ. Res. Lett.* **11**, 095009 (2016).
- Burkholz, R. & Schweitzer, F. International crop trade networks: the impact of shocks and cascades. *Environ. Res. Lett.* **14**, 114013 (2019).
- Heslin, A. et al. Simulating the cascading effects of an extreme agricultural production shock: global implications of a contemporary US Dust Bowl event. *Front. Sustain. Food Syst.* **4**, 26 (2020).
- Grassia, M., Mangioni, G., Schiavo, S. & Traverso, S. Insights into countries' exposure and vulnerability to food trade shocks from network-based simulations. *Sci. Rep.* **12**, 4644 (2022).
- Distefano, T., Laio, F., Ridolfi, L. & Schiavo, S. Shock transmission in the international food trade network. *PLoS ONE* **13**, 0200639 (2018).
- Schewe, J., Otto, C. & Frieler, K. The role of storage dynamics in annual wheat prices. *Environ. Res. Lett.* **12**, 054005 (2017).
- Falkendal, T. et al. Grain export restrictions during COVID-19 risk food insecurity in many low- and middle-income countries. *Nat. Food* **2**, 11–14 (2021).
- Galbusera, L. & Giannopoulos, G. On input–output economic models in disaster impact assessment. *Int. J. Disaster Risk Reduct.* **30**, 186–198 (2018).
- Miller, R. E. *Input–Output Analysis: Foundations and Extensions* (Cambridge Univ. Press, 2021); <https://doi.org/10.1017/9781108676212>
- Bruckner, M. et al. FABIO—the construction of the food and agriculture biomass input–output model. *Environ. Sci. Technol.* **53**, 11302–11312 (2019).
- Sun, Z., Scherer, L., Tukker, A. & Behrens, P. Linking global crop and livestock consumption to local production hotspots. *Glob. Food Secur.* **25**, 100323 (2020).
- Pichler, A. & Farmer, J. D. Simultaneous supply and demand constraints in input–output networks: the case of COVID-19 in Germany, Italy, and Spain. *Econ. Syst. Res.* **34**, 273–293 (2022).
- FAOSTAT: *Trade of Crops and Livestock Products* (FAO, accessed 13 May 2022); www.fao.org/faostat/en/#data/TCL
- Yang, L., Laber, M., Klimek, P., Bruckner, M. & Thurner, S. *Food Supply Shock Explorer* (Complexity Science Hub, accessed 5 March 2023); <https://vis.csh.ac.at/food-supply-shocks/>
- Abay, K. A. et al. The Russia–Ukraine war: implications for global and regional food security and potential policy responses. *Glob. Food Secur.* **36**, 100675 (2023).
- Behnassi, M. & El Haiba, M. Implications of the Russia–Ukraine war for global food security. *Nat. Hum. Behav.* **6**, 754–755 (2022).
- Mottaleb, K. A., Kruseman, G. & Snapp, S. Potential impacts of Ukraine–Russia armed conflict on global wheat food security: a quantitative exploration. *Glob. Food Secur.* **35**, 100659 (2022).
- Shiferaw, B. et al. Crops that feed the world 10. Past successes and future challenges to the role played by wheat in global food security. *Food Sec.* **5**, 291–317 (2013).
- Shiferaw, B., Prasanna, B. M., Hellin, J. & Bänziger, M. Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. *Food Sec.* **3**, 307–327 (2011).
- Osendarp, S. et al. Act now before Ukraine war plunges millions into malnutrition. *Nature* **604**, 620–624 (2022).
- Gomez, M., Garcia, S., Rajtmajer, S., Grady, C. & Mejia, A. Fragility of a multilayer network of intranational supply chains. *Appl. Netw. Sci.* **5**, 71 (2020).
- Naqvi, A. & Monasterolo, I. Assessing the cascading impacts of natural disasters in a multi-layer behavioral network framework. *Sci. Rep.* **11**, 20146 (2021).
- Sartori, M. & Schiavo, S. Connected we stand: a network perspective on trade and global food security. *Food Policy* **57**, 114–127 (2015).
- Diem, C., Borsos, A., Reisch, T., Kertész, J. & Thurner, S. Quantifying firm-level economic systemic risk from nation-wide supply networks. *Sci. Rep.* **12**, 7719 (2022).

41. Obersteiner, M., Peñuelas, J., Ciais, P., van der Velde, M. & Janssens, I. A. The phosphorus trilemma. *Nat. Geosci.* **6**, 897–898 (2013).
42. Barbieri, P., MacDonald, G. K., de Raymond, A. & Nesme, T. Food system resilience to phosphorus shortages on a telecoupled planet. *Nat. Sustain.* **5**, 114–122 (2022).
43. Bubola, E., Safronova, V. & Varenikova, M. ‘Everything was destroyed’: war hits Ukraine’s farms. *New York Times* (10 April 2022); <https://www.nytimes.com/2022/04/10/world/europe/ukraine-farmers-food.html>
44. Reed, J. et al. How Russia’s war in Ukraine upended the breadbasket of Europe. *Financial Times* (accessed 27 April 2022); <https://ig.ft.com/ukraine-war-food-insecurity/>
45. Davis, K. F., Downs, S. & Gephart, J. A. Towards food supply chain resilience to environmental shocks. *Nat. Food* **2**, 54–65 (2021).
46. Laber, M. Input data and code for shock propagation from the Russia–Ukraine conflict on international multilayer food production network determines global food availability. *GitHub* <https://github.com/L-MoNi/shock-propagation-food-supply> (2023)

Acknowledgements

We are grateful to C. Diem, T. Reisch, A. Pichler, J. Hurt and F. Neffke for illuminating discussions. This work was supported by the Austrian Science Promotion Agency FFG under 882184 (S.T.) and 886360 (S.T.) and by the Austrian Science Fund FWF under P 31598-G31 (M.B.).

Author contributions

P.K., M.L. and S.T. contributed to study conception and design. Data were collected by M.B. Analysis was carried out by M.L. Results were interpreted by P.K., M.L. and S.T. The artwork was conceived by L.Y. and M.L. The first draft of the manuscript was written by M.L., and

all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s43016-023-00771-4>.

Correspondence and requests for materials should be addressed to Stefan Thurner.

Peer review information *Nature Food* thanks Megan Konar, Antoine Bernard de Raymond and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

© The Author(s), under exclusive licence to Springer Nature Limited 2023

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our [Editorial Policies](#) and the [Editorial Policy Checklist](#).

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a | Confirmed

- The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
- A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
- The statistical test(s) used AND whether they are one- or two-sided
Only common tests should be described solely by name; describe more complex techniques in the Methods section.
- A description of all covariates tested
- A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
- A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
- For null hypothesis testing, the test statistic (e.g. F , t , r) with confidence intervals, effect sizes, degrees of freedom and P value noted
Give P values as exact values whenever suitable.
- For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
- For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
- Estimates of effect sizes (e.g. Cohen's d , Pearson's r), indicating how they were calculated

Our web collection on [statistics for biologists](#) contains articles on many of the points above.

Software and code

Policy information about [availability of computer code](#)

Data collection

Data analysis

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio [guidelines for submitting code & software](#) for further information.

Data

Policy information about [availability of data](#)

All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our [policy](#)

Human research participants

Policy information about [studies involving human research participants and Sex and Gender in Research](#).

Reporting on sex and gender	<input type="text" value="not applicable"/>
Population characteristics	<input type="text" value="not applicable"/>
Recruitment	<input type="text" value="not applicable"/>
Ethics oversight	<input type="text" value="not applicable"/>

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

Life sciences Behavioural & social sciences Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see [nature.com/documents/nr-reporting-summary-flat.pdf](https://www.nature.com/documents/nr-reporting-summary-flat.pdf)

Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	<input type="text" value="We did not collect data by means of survey or experiment."/>
Research sample	<input type="text" value="not applicable"/>
Sampling strategy	<input type="text" value="not applicable"/>
Data collection	<input type="text" value="not applicable"/>
Timing	<input type="text" value="not applicable"/>
Data exclusions	<input type="text" value="not applicable"/>
Non-participation	<input type="text" value="not applicable"/>
Randomization	<input type="text" value="not applicable"/>

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involvement in the study
<input checked="" type="checkbox"/>	<input type="checkbox"/> Antibodies
<input checked="" type="checkbox"/>	<input type="checkbox"/> Eukaryotic cell lines
<input checked="" type="checkbox"/>	<input type="checkbox"/> Palaeontology and archaeology
<input checked="" type="checkbox"/>	<input type="checkbox"/> Animals and other organisms
<input checked="" type="checkbox"/>	<input type="checkbox"/> Clinical data
<input checked="" type="checkbox"/>	<input type="checkbox"/> Dual use research of concern

Methods

n/a	Involvement in the study
<input checked="" type="checkbox"/>	<input type="checkbox"/> ChIP-seq
<input checked="" type="checkbox"/>	<input type="checkbox"/> Flow cytometry
<input checked="" type="checkbox"/>	<input type="checkbox"/> MRI-based neuroimaging