Resources, Conservation & Recycling 188 (2023) 106657

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Influence of Russia-Ukraine War on the Global Energy and Food Security

Xi-Yin Zhou[a,*], Gang Lu[b], Zhicheng Xu[b], Xiaoqing Yan[b], Soon-Thiam Khu[c], Junfeng Yang[d], Jian Zhao[e,**]

[a] School of Systems Science, Beijing Normal University, Beijing 100875, PR China
[b] State Grid Energy Research Institute CO., Ltd., Beijing, 102209, PR China
[c] School of Environmental Science and Engineering, Tianjin University, Tianjin 300350, PR China
[d] China Center for Information Industry Development, 100048, China
[e] State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, No.8 Anwain Dayangfang Road, Beijing 100012, China

ARTICLE INFO

Keywords:
Russian and Ukraine War
Cascading Failure
Robustness
Resilience

ABSTRACT

The Russian- Ukraine War has and further influence the global energy and food security. However, the detailed influence degree, key weak points and influence process is still unclear in the current. Therefore, this study established a newly improved under-load cascading failure model with consideration of overload limitation, and used it to evaluate influence of Russian- Ukraine War on the global energy and food security. This study also proposed a method to assess the network structure characteristic including robustness and resilience through model simulation under different scenarios. The main results include: The upper limitation of node load has the dominant function on the global energy and food security, while the influence of lower limitation parameter of node load has limited function. All of the networks have relative consistent recover and anti-damage ability against Russian and Ukraine War and the global panic except barley network. A key phenomenon we should concern is that the largest trade flow amounts are not occurred in the failure nodes. The failure nodes are always the countries with low economic scale and political status. The results tell us that we should further strengthen the importance of enhance production ability and energy types to resist the risk of Russian and Ukraine War. The global international organizations are also required to strengthen the function of balance the global security demand of energy and food between big countries and small countries. We should pay more attention to the little countries in the Africa and Asia to handle the risk.

1. Introduction

The world is in a fragile state under the long-term pressure from the COVID-19 pandemic in each field such as energy and food (Kruczkiewicz et al., 2021). The Russian invasion of Ukraine, occurred between two main exporters of food and energy in the world would even worsen the global energy and food security (Mbah and Wasum, 2022). The Russia-Ukraine War (RUW) has actually induced roaring cereal and oil prices, and global inflation (Deng et al., 2022). Tollefson (2022) believed that although RUW has caused a short-term prices increase, it would be a chance to prompt a long-term shift towards energy sustainability.

Many academics, government officials and journalists have discussed the influence of RUW on energy and food security (Benton et al., 2022). However, they are mainly discussed based on expert judgment, without a suitable model analysis tool. The influence of RUW on energy and food are mostly explored in the regional level such as European Union (Blanchard and Pisani-Ferry., 2022), Morocc (Mengoub et al., 2022), Indian (Meena, 2022), Azerbaijan (Mammadov, 2022), China (Oxford Analytica, 2022a), Japan (Oxford Analytica, 2022b).

In the context of economic globalization, the supply and demand of food and energy between each country are closed linked (D`Odorico et al., 2018; Ruhl., 2019 Gaupp, 2020). The regional element corruption would cause global disaster in the complex network, which is called cascading failures (Lee and Goh., 2016). The cascading failures process has been revealed in the networks such as physical infrastructure networks (Guo et al., 2017; Liu et al., 2021), economic and finance network (Havlin and Kenett., 2015; Smolyak et al., 2018), and internet network

* Corresponding author.
** Corresponding author.
E-mail addresses: zhouxiyin@bnu.edu.cn (X.-Y. Zhou), zhaojianzhaoj@163.com (J. Zhao).

https://doi.org/10.1016/j.resconrec.2022.106657
Received 14 June 2022; Received in revised form 30 August 2022; Accepted 8 September 2022
Available online 21 September 2022
0921-3449/

(Xing, 2020; Ren et al., 2018). Take the economic trade network as an example, the cascading failures process can be described as below: Once a country has a supply or demand problem of a product, then a global cascading failure is triggered in the trade network due to the global economic trade relationship. The cascading failures types including edge-based-attack cascading failures and node-based-attack cascading failures (Li et al., 2012; Zhu et al., 2014). The simple occurrence mechanism is that under the initial attack, the load of the attacked node or edge would be distributed to its neighbors, and once the load of neighbors is larger compared with their load capacity, the neighbors are destroyed, and finally caused network cascading failure (Zhao et al., 2016). In some cases such as supply chain networks, the underload cascading failures process would be considered, which indicates that under the initial attack, due to lack of the load supply of the targeted node or edge, the load of the neighbors is reduced and once lower with the underload capacity, the neighbors are destroyed, and finally caused network cascading failure (Yang et al., 2021).

However, the cascading failures method is still few used in the research of global food or energy trade system, let alone the coupled food-energy system. The current cascading failures analysis barely consider the overload status and underload status at the same time. In the single food trade system, the lack of a main food exporter country would not cause food security risk of targeted importer countries, the food security risk of targeted importer countries would induce secondary food risk of other countries. So as the single energy trade system. What's more, due to the economic globalization, the basic primary industry-food system, and the basic secondary industry-energy system also have closed linkages, and have key influence on the whole economic system of a certain country. One system breakdown would cause the disruption of the other system. The cascading failures method is also a suitable tool to assess the influence of war on the global energy and food trade systems, which is still few can be found in the current research.

Academics have agreed that RUW would cause global food and energy crisis (Benton et al., 2022; Osendarp et al., 2022; Żuk and Żuk, 2022). However, there is still limited understanding of how RUW would influence the global energy and food security and ways to design an alternative means to mitigate the influence. To help address this gap, we construct a global energy and food network that includes approximately 238 countries, three main types of energy and three main types of cereals, so as the coupled energy and food networks. We create and improve an underload cascading failure with consideration of overload limitation to assess the influence of RUW on the global energy and food security. To fill the existing gap between knowledge and practice on this topic, a scenario analysis is also used to reveal the global energy and food security risks due to RUW through comparing different capacity and load change and coupling modes to answer some important questions: What would RUW bring to the global energy and food security? What is the cascading failure process caused by RUW? Which are the key and vulnerable countries that would be hurt by RUW? What are the best means to mitigate the influence of RUW? Our findings offer significant new insights that can reveal the impact degree of RUW and enable policymakers to identify potential solutions to this global crisis.

2. Materials and methods

2.1. Global Network Data

According to the UN Comtrade Database, complex trade networks of energy and food covering all import and export flows occurring between 238 countries in 2020 have been developed. We downloaded data on "cereals" and "fossil fuels" on May 1st, 2020. To avoid double counting between exporter and importer, which named reporter and partner in the UN Comtrade Database, the information on the importers is extracted as import data are usually more accurate (Shi et al., 2021). Furthermore, in the energy trade network, the more specific energy types of coal, oil and gas are chosen to reveal their cascading failure process. In the food trade network, only the cereals are considered, especially barley, maize and wheat. The energy trade network and food trade network are integrated according to the energy equivalent (Tiewsoh et al., 2017)

2.2. Improved Cascading Failure Model

There are two basic cascading failure modes, one is overload cascading failure, which is often used in infrastructure networks, and the other one is under-load cascading failure, which is used in supply networks. A complex network usually considers one kind of cascading failure mode at the same time. The initial load, the capacity, the distribution rule, and the failure rule are the four basic components of a cascading failure model of a complex network (Wang et al., 2018). This study establishes a newly improved under-load cascading failure model with consideration of overload limitation (OLUCF). The main improvement is that the model considers the under-load limitation and overload limitation at the same time. However, different from the existed cascading failure model, the overload limitation would not induce nodes failure, the main function of overload limitation is that the surplus load compared with the overload capacity would be canceled. Only the actual load is lower than the under-load limitation, then the cascading failure process will be stimulated. The reason is that in the real energy and food systems, each country has its upper-limitation of production and consumption, once the actual load exceeds the upper-limitation, they have trade amount self-adjustment ability when the load is too high rather than destroy themselves. However, under the background of economic globalization, once the actual load is lower than the lower-limitation requirement, as the basic supply sector in the economy system, the lack of the adequate energy and food will destroy the country economy, and cause the cascading failure process.

In the OLUCF, only the loads of nodes are considered in the initial load and capacity determination firstly. Then, to simulate the influence of RUW, the nodes of Russian and Ukraine will be disrupted. During the load distribution process, both the loads of nodes and edges will be considered. During the distribution process, the export amount from Russian or Ukraine will be distributed to other edges from other exporter countries which has trade relationship with the targeted importer country according to their initial loads proportionally. Furthermore, the upper-limitation of node load capacity will be assigned to each edge according to their initial loads proportionally. Once an edge's load exceeds its upper-limitation, the surplus amount will be distributed to other edges from other countries which has trade relationship with the targeted importer country. Then, subsequent overloads may occur. Finally, after all the surplus capacity of other available nodes are distributed, the undistributable trade amount will be deleted directly. Then the failure rule may be triggered by the failed nodes, while the export amount of export country or import amount of import country is less than the minimum capacities, are forbidden from importing or exporting food or energy. The dynamic progression of the OLUCF is illustrated in Fig. 1.

In the step1, we use the export amounts of countries to measure the initial load. The capacity of each country has upper and lower limits.

$$\mathrm{L0_i} = Export_i \tag{1}$$

$$\mathrm{NC_{i(max)}} = \alpha \mathrm{L0_i},\ \alpha \geq 1 \tag{2}$$

$$\mathrm{NC_{i(min)}} = \begin{cases} \beta \mathrm{L0_i}, & 0 < \beta < 1,\ Export_i > Import_i \\ \beta Import_i, & 0 < \beta < 1,\ Export_i < Import_i \end{cases} \tag{3}$$

In which, $NC_{i(max)}$ indicates the upper limit of node ***i, NCi(min)*** indicates the lower limit of node *i*, $L0_i$ indicates the initial load of node *i*, $Export_i$ indicates the export amount of food or energy of node i, $Import_i$ indicates the import amount of food or energy of node i, α indicates the fixed upper limit parameter, β indicates the fixed lower limit parameter.

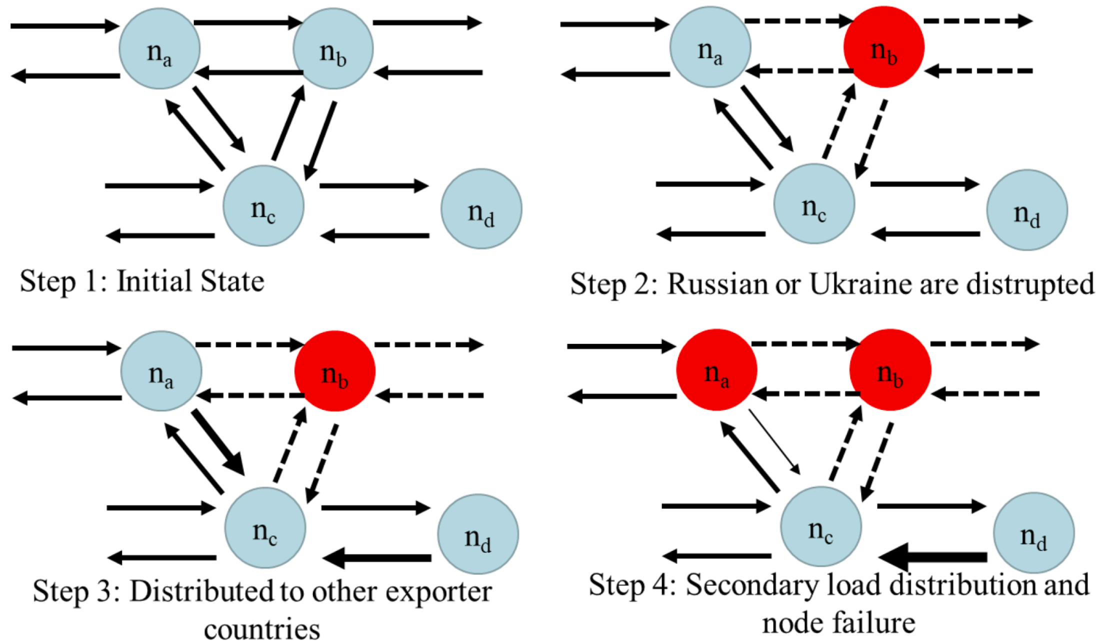

Fig. 1. Cascading failure process of the OLUCF

In the step 2 and step 3, once Russian and Ukraine are disrupted, the export amount from them will be distributed to other edges from other exporter countries which has trade relationship with the targeted importer country according to their initial loads proportionally.

$$EW_{kt} = EW_{kt0} + EW_{nt} \times \frac{EW_{kt0}}{\sum_{j=1}^{b} EW_{jt0}} \tag{4}$$

In which, n indicates node Russian or Ukraine, t indicates countries that import food or energy from Russian or Ukraine, k indicates countries that export food or energy to t except Russian or Ukraine, b indicates the amount of nodes from node k to t, EW_{kt0}indicates the initial edge load from node k to t, EW_{nt} indicates the initial edge load from node n to t, $\sum_{j=1}^{b} EW_{kt0}$ indicates the summation of the initial edge load from all nodes j to t, EW_{kt} indicates the edge nodes from k to t after load redistribution.

In the step 4, the secondary load distribution happened, the upper-limitation of node load capacity will be assigned to each edge according to their initial loads proportionally.

$$EC_{kt} = \mathrm{NC}_{\mathrm{k(max)}} \times \frac{EW_{kt0}}{\sum_{j=1}^{b} EW_{kt0}} \tag{5}$$

$$EC_{mt} = \mathrm{NC}_{\mathrm{m(max)}} \times \frac{EW_{mt0}}{\sum_{j=1}^{b} EW_{mt0}},\ m \neq k \tag{6}$$

$$EW_{kt} = \begin{cases} EW_{kt},\ \ EW_{kt} < EC_{kt} \\ EC_{kt},\ EW_{kt} > EC_{kt} \end{cases} \tag{7}$$

$$EW_{mt} = \begin{cases} EW_{mt} + (EW_{kt} - EC_{kt}) \times \dfrac{EW_{mt0}}{\sum_{j=1}^{b} EW_{mt0}}, EW_{kt} > EC_{kt}, EW_{mt} < EC_{mt} \\ EC_{mt}, EW_{kt} > EC_{kt} \end{cases} \tag{8}$$

In which, EC_{kt} indicates upper-limitation of edge load from k to t, EC_{mt} indicates upper-limitation of edge load from m to t, EW_{mt} indicates edge load from m to t.

Finally, after all the surplus capacity of other available nodes are distributed, the undistributable trade amount will be deleted directly. Then if the export amount of export country or import amount of import country m in the energy or food network is lower than the lower limitation of node m, the failure rule will be triggered by the failed nodes m, which are forbidden from importing or exporting food or energy.

To further reveal the possible coupling relationship between energy and cereals network, and its influence on global energy and cereals network. The coupling parameter between energy and food networks is proposed, and simulated in OLUCF. It indicates that for the same country, if its node load in the energy or food network is lower than the limitation of the coupling value, then, the node in the other network would be destroyed, no matter what the current node load is. It can be recognized a new way to simulate cascading failure in the interdependent networks with consideration of the simple relationship of symbiotic relationship, which is different from the previous method that focus on the edges establishment and weight calculation.

In addition, this study proposed a method to assess the network structure characteristic including robustness and resilience, through OLUCF simulation under different scenarios. The network robustness strength means the ability to maintain its structure against RUW, which is assessed through the following formula:

$$NRO = \frac{\mathrm{NEN}_{\alpha=1}}{TN},\ \alpha = 1 \tag{9}$$

In which, $NEN_{\alpha=1}$ indicates the effective nodes number in the network after cascading failure simulation which α is set as 1, TN indicates the total nodes number in the network, NRO indicates the network robustness strength.

The network resilience assessment including the resilience with only consideration of the upper limitation increase of node load induced by direct influence of RUW (NRE_d)and the resilience with consideration of the upper limitation decrease of node load and node load increase induced by the indirect influence from global panic of RUW (NRE_{in}). NRE_d indicates the recover ability of the network against RUW, and NRE_{ind} indicates the anti-damage ability against RUW and global panic.

$$NRE_d = \frac{\mathrm{NEN}_{\alpha=\mathrm{a}}}{TN} - NRO\,(a\ >\ 1) \tag{10}$$

$$NRE_{ind} = \frac{\mathrm{NEN}_{\alpha=\mathrm{b}}}{TN} - NRO\,(0 < b <\ 1) \tag{11}$$

In which, $NEN_{\alpha=a}$ indicates the effective nodes number in the network after cascading failure simulation which α is set as a, $NEN_{\alpha=b}$ indicates the effective nodes number in the network after cascading failure simulation which α is set as b. The higher value of NRE_d and NRE_{ind} indicates the better resilience against RUW and the global panic. The α value is obtained from the node load change ratio in the real network. In this study, in order to exclude the impact of COVID-19, the actual historical trade change trend from the most recent years of 2018-2019 is adopted, we can find that most of the change ratio compared with the current node load are in the range of 0.5-1.5, which is accounted for 71.90% at least (table 1). Therefore, the value of α is set as 1.5 to calculate NRE_d and is set as 0.5 to calculate NRE_{ind}. Researchers can adopt their suitable α value according to their research requirement.

2.3. Scenarios design

To observe the possible risk of RUW on the global food and energy security, four types of cascading failure modes are simulated with different node load and capacity change rules, and network coupling rules (table 2). The scenarios are set according to the parameters chosen and value assignment. Furthermore, in the energy trade network, the more specific energy types of coal, oil and gas are chosen to reveal their cascading failure process. In the food trade network, only the cereals are considered, especially barley, maize and wheat.

The node load indicates the total energy or food exports amount of a country. The upper limitation of node load is assumed to be related with the node load, it will increase 0 %-50% compared with current node load in the upper limitation increase scenario and decrease 0 %-50% compared with current node load in Load increase-Upper limitation decrease scenario. Coupling parameter between food and energy network. To identify the influence of coupling effect between energy and food network on the global energy and food security, we assumed that for the same country, if its node load in the energy or food network is lower than the limitation of the coupling value, then, the node in the other network would be destroyed, no matter what the current node load is. Therefore, it should be a low value which indicates that the coupling cascading failure process is not easy happened in the interdependent network. Therefore, the change range of the coupling parameter is set between 0-0.4. Lower limitation of node load is a key parameter that induced the cascading failure process in this process. It is also the main improvement of OLUCF compared with the existed cascading failure mode. Only the actual node load is lower than the under-load limitation, then the cascading failure process will be stimulated which is more in line with reality. Once the actual load is lower than the lower-limitation requirement, as the basic supply sector in the economy system, the lack of the adequate energy and food will destroy the country economy, and cause the cascading failure process. The change range of the lower limitation of node load is set between 0.1-0.6. To observe the critical threshold of the influence of each parameter on the global energy and food network, the parameters value is set as a series of number in a certain range. Then, the cascading failure results with each parameters value combination can be obtained. The critical threshold value can provide suggestions for risk identification and prevention of global energy and food security.

The first two scenarios are simulated in all of energy network including coal, oil, gas, and the integrated energy network, and food network including barley, maize, wheat and the integrated cereals network. In the first scenario of upper limitation increase of node load, we will observe the influence change of RUW on the global food and energy security along with the countries' production ability increase and the ability to resist risk of import and export ratio decrease. The production ability increase can be presented by the parameter value increase of upper limitation of node load, and the ability to resist risk of import and export ratio decrease can be indicated by the parameter value increase of the lower limitation of node load. The second scenario of load increase and upper limitation decrease is established based on the assumption that to prevent the hurt of global panic induced by the RUW on the local food and energy security, the import country would increase their import demand, and the export country would decrease their exporter demand. The difference compared with the first scenario is that the parameter of node load increases

The last two scenarios are only simulated in the integrated energy and cereals network, which assumed that the node failure in the integrated energy or cereals network would induce the node failure in the other network, which can be recognized as cascading failure in interdependent networks (Duan et al., 2019). In this study the cascading failure process in interdependent networks happened through the coupling parameters of food and energy networks. The third scenario is based on the first scenario with consideration of the coupling process between food and energy networks. The fourth scenario is based on the second scenario with consideration of the coupling process between food and energy networks. The coupling effect is presented by the value of coupling parameter between food and energy network. The higher of the value, the easier happen of the coupling cascading failure process in the interdependent networks.

Table 1
Frequency distribution of α value in the energy and food network

Range	Energy			Food		
	Coal	Gas	Oil	Barley	Maize	Wheat
<0.5	6.25%	8.65%	9.39%	14.77%	8.96%	10.46%
<1.5&>0.5	78.13%	75.00%	80.11%	73.86%	72.39%	71.90%
>1.5	15.63%	16.35%	10.50%	11.36%	18.66%	17.65%

3. Results and Discussion

3.1. Global energy and cereals contribution of Russian and Ukraine

It can be found that Russian and Ukraine contributes 12.09% to the global energy trade, while Russian accounted for 12.01%. Fig. 2 shown that the countries with highest imports percentage from Russian were mostly located in the Europe and Asia. It also indicates that they may more easily been influenced by RUW. Focusing on specific energy types, it can be found that Russian and Ukraine contributes 15.60% to the global coal trade, 11.34% to the global oil trade and 10.00% to the global gas trade, while Russian accounted most of the export amount.

In the global cereals trade network, the pattern is quite different from the energy network. It can be found that Russian and Ukraine contributes 18.83 % to the global cereals trade, while Russian and Ukraine nearly accounted for the same ratio. Fig. 2 shown that the countries with highest imports percentage from Russian and Ukraine were mostly located in the Africa, Europe and Asia. It also indicates that they may more easily been influenced by RUW. Focusing on specific cereals types, it can be found that Russian and Ukraine contributes 19.55% to the global barley trade, 14.44% to the global maize trade and 10.00% to the global wheat trade, while Russian accounted most of the export amount. While for barley, the nearly accounted for the same ratio, for maize, Ukraine accounted most of the contribution, and for wheat, Russian accounted for the 66.66% among the contribution of them.

From the view of exports countries of cereals and energy from Russian and Ukraine, it can be found that they are mostly of the countries with relative lower economy scale. The export amounts of energy only accounted for 6.30% of the total imports amount of the United States, and 12.68 in China, which are mainly come from Russian. While for cereals, they only accounted for 0.17% in the United States and 23.11 % in China, which are mainly come from Ukraine.

3.2. Influence of RUW on global energy security

Influence of RUW on global energy trade network can be found through OLUCF simulation under different scenarios. While LLNL is

Table 2
Scenarios design

Parameters Scenarios	Network	Upper limitation of node load (ULNL)	Node load (NL)	Coupling parameter between food and energy network	Lower limitation of node load (LLNL)
Upper limitation increase scenario (ULIS)	Coal, oil, gas and the integrated energy network, barley, maize, wheat and the integrated cereals network	Increase (0-0.5)	Constant	-	Increase(0.1-0.6)
Load increase-Upper limitation decrease scenario (LIULDS)		Decrease(0-0.5)	Increase(0-0.5)	-	Increase(0.1-0.6)
ULIS with consideration of Coupling	The integrated energy and cereals network	Increase (0-0.5)	Constant	Increase (0-0.4)	Increase
LIULDS with consideration of Coupling		Decrease (0-0.5)	Increase(0-0.5)	Increase (0-0.4)	Increase(0.1-0.6)

determined, it can be found that along with the increase of upper- limitation of node load, the number of retained countries become more. Once the upper-limitation increase to 120% of the current node load, all of the four types of energy network would maintain 80% of the countries. The integrated energy network and oil trade network have the strongest robustness against RUW, they can maintain more than 80% of the countries, even though other countries have no extra production ability. while coal trade network is more easily influenced by RUW, once other countries have no extra coal production ability, only 42.92% of the countries are left in the network. Furthermore, the existed countries number of integrated energy network, oil trade network and gas network would recover to 94.12%, 93.67% and 80.70% while ULNL increase to 105%, and it requires ULNL increase to 115% to maintain the existed countries number of coal network at a high level. Therefore, RUW have more influence on coal and gas trade network than oil network. Through the separate simulation of node failure of Russian and Ukraine, it can be found that it is Russian that mainly influence the global energy trade network. Through observation of the influence change along with LLNL increase while ULNL is equal to 0.3, it can be found that due to the adequate upper limitation of node load, the LLNL change has little influence on global energy network. There is still more than 92.52% existed in the network under attacks. Among them, the gas and coal trade networks are more easily influenced by LLNL change, it indicates that the average exports amount percentages of gas and coal contributes from Russian are higher than oil and the integrated energy.

Under the LIULDS, it can be found that RUW would produce much larger influence than their actual energy export amount due to amplification effect of energy demand and storage from fears of energy shortages. The integrated energy trade network and oil trade network presented their strong robustness against RUW that they can still maintain more than 40. 75% of the countries while the node load increase to 50 %, the upper limitation of node load decrease to 50 %, and LLNL is equal to 0.4. The coal and gas network can only maintain 9.13 % and 3.95 % of the countries in the final. While ULNL is equal to 0.3, it can be found that the coal and gas trade network would be nearly destroyed dramatically, the effective countries of the integrated energy and oil trade network would be also reduced significantly, which only 57.14 % and 61.18 % of the countries are maintained.

Through comparison of Fig. 3a, 3b and 3c,3d, it can be concluded that the vulnerability of the gas trade network is the highest, once the network upper limitation is reduced and the node load increase, it will be easily influenced by RUW. However, it also has relative strong resilience, once the upper limitation of node load increase 5%, then the effective nodes ratio will increase from 55.70 % to 80.70 %. The parameter of upper limitation of node load has the dominant function on the global energy security, while the influence of lower limitation parameter of node load has limited function. Under ULIS, which is the optimistic and simple scenario, if all of the energy exporter countries own more than 15% surplus production ability, all of the four types of energy network can maintain at least 87.72% of the country nodes. However, under LIULDS, which can be recognized as the extreme situation caused by the global energy security, the global energy trade network can be hurt obviously, especially the coal and gas trade network. During RUW, the energy exports change of Russian plays the key role on the global energy trade network compared with Ukraine, which is consistent the results of the 3.1 section.

3.3. Influence of RUW on global cereals security

The Influence of RUW on global cereals trade network can be assessed through OLUCF simulation under different scenarios. While LLNL is set 0.4, the increase of upper-limitation of node load would recover the effective country nodes of the cereals network. Among the four types of cereals network, the integrated cereals network can recover most quickly following by maize trade network, while there are 20% surplus capacity of other countries, they can reserve 97. 47 % and 92.00% of the total country nodes separately. The wheat trade network is influenced most significantly by RUW. Until there are 35% surplus capacity of other countries, it can reserve 91.73% effective country nodes. Specially, the influence of RUW on the barley trade network is limited, and have little recovery along with the increase of upper limitation of node load, it indicates that in the barley trade network, the export destination countries from Russian and Ukraine is limited, so as the import sources diversity of the countries which import barley from Russian and Ukraine. Therefore, RUS can only destroy restricted country numbers, and these countries are not easy obtain barley from other countries. Russian has greater influence on wheat trade network, while Ukraine has greater influence on maize trade network. Through observation of the influence change along with LLNL increase while ULNL is equal to 0.3, it can be found that RUW has more obvious influence on the cereals network, especially the wheat trade network compared with the energy trade network. The cereals trade network requires more upper limitation of node loads in order to protect the network integrity compared with the energy trade network. What is more, RUW would induce the wheat supply of 20 % of the total countries less than 40 %.

Fig. 4c presents some different results compared with the energy network. In the energy network, gas network is most significantly influenced by RUW under ULIS and LIULDS. In the cereals network, the wheat network shows its vulnerability and the barley network shows its robustness facing RUW under ULIS. However, under LIULDS, along with the upper limitation of node load decrease and node load increase, the barley network present opposite characteristic. The reason is that, the barley trade network is little relied on Russian and Ukraine and is strongly relied on other countries. The global scare of food shortage induced by RUW would change the upper limitation of food export amount, although RUW could not directly influence the global barley trade network. The indirect influence of RUS would significantly hurt the export amount from other countries, and finally lead to the collapse of barley network. The maize trade network has nearly the same characteristic with the barley network, while the wheat network shows opposite characteristic that has relative vulnerability under ULIS and robustness under LIULDS. The integrated cereals networks maintain strong robustness under the two scenarios. The parameter of upper limitation of node load has the dominant function on the global cereals

Fig. 2. The imports percentage of top 15 countries with highest contribution of food and energy, United States and China from Russian and Ukraine

security, while the influence of lower limitation parameter of node load has more obvious function compared with the energy trade network.

3.4. Influence of RUW on global coupled energy and cereals security

In the current coupling effect research of energy and food systems, they are mainly carried out from the area of water–energy–food nexus research based on the methods of integrated index, computable general equilibrium model, ecological network analysis, life-cycle analysis, input-output analysis, system dynamics model, agent-based modeling, etc (Endo et al., 2020). They can reveal overall status of coupled energy and food systems, and the linkage strength between energy and food systems. The coupling effect are revealed based on the indicators correlation and flow amount. However, the cascading failure mode have

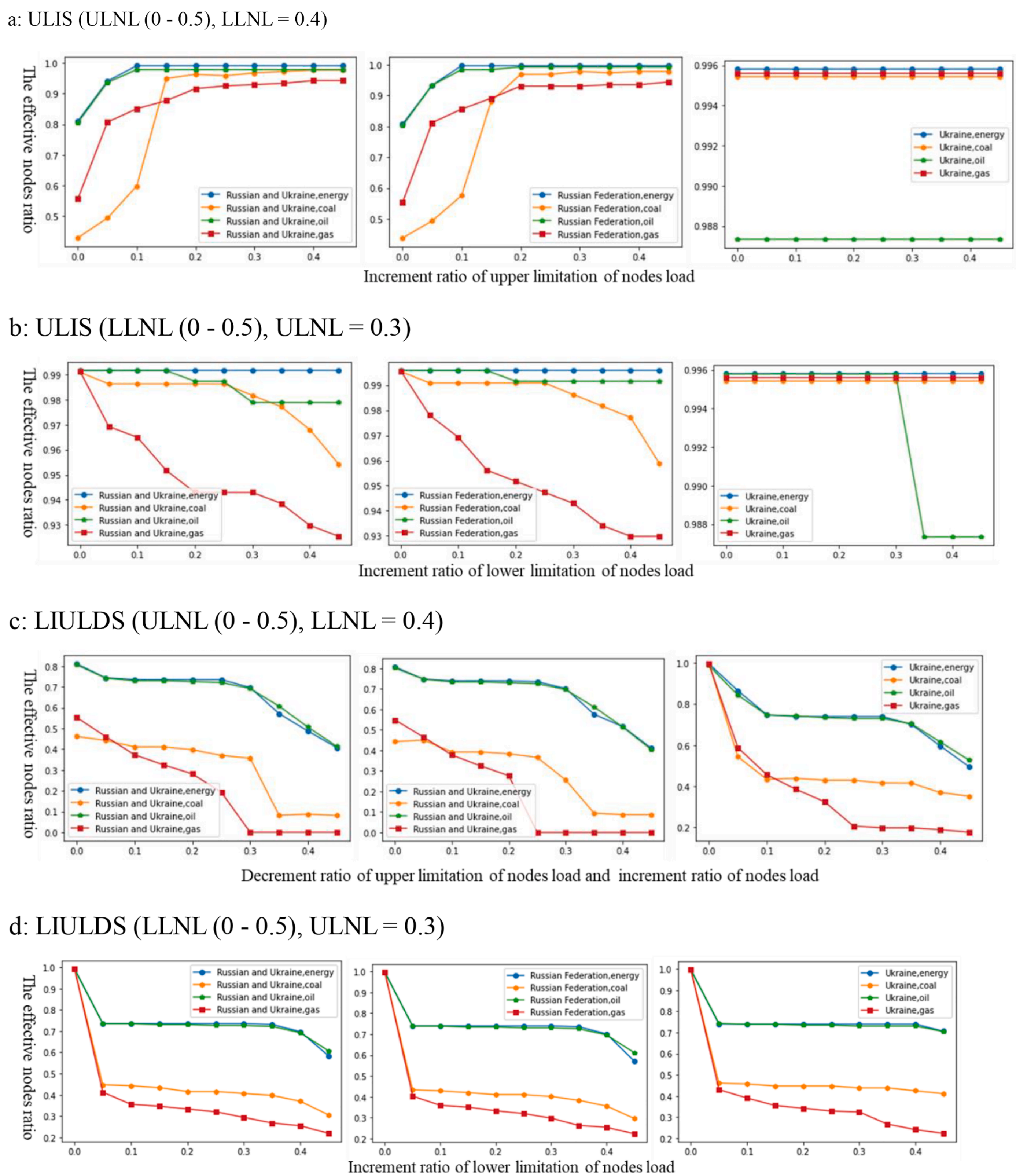

Fig. 3. Influence of RUW on global energy trade network under ULIS and LIULDS

not been used in the coupled effect research of energy and food systems. OLUCF can reveal the robustness, resilience, and the ability to resist risk of the energy and food network, and can also identify the influence of a certain disaster on the energy and food network through simulated strike. The results can provide direct support for global energy and food security management. The coupling parameter is firstly proposed to observe the influence of coupling effect of energy and food systems on the global energy and food security. We assumed the possible coupling strength between energy and food networks, then, we observed that under the specific coupling parameter value, what would happen to the coupled energy and food networks, and the influence on the global energy and food security. The results can tell us what is the influence

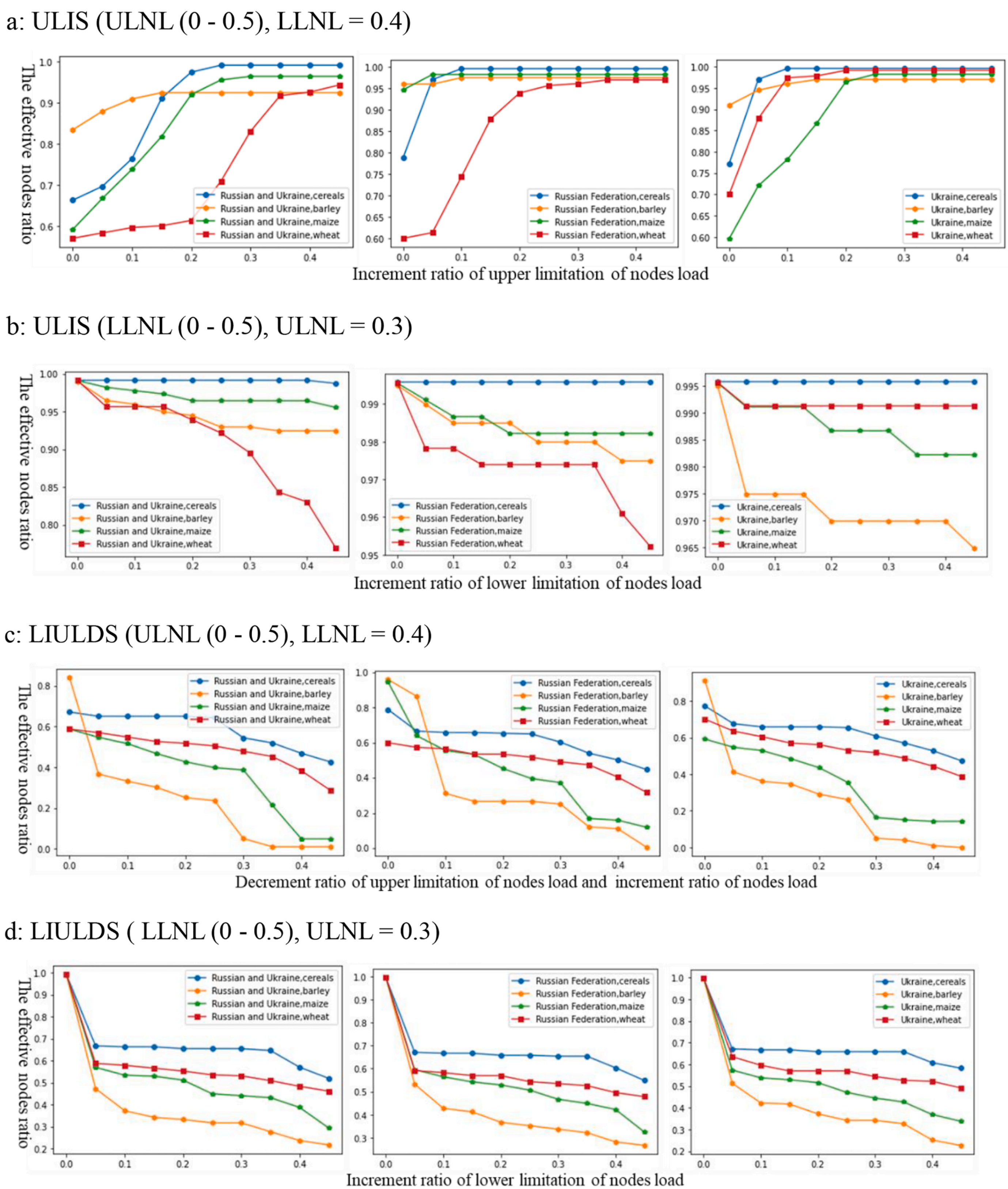

Fig. 4. Influence of RUW on global cereals trade network under ULIS and LIULDS

extent that the coupling effect would bring to the global food and energy systems, the possible risky nodes and risk transfer path, and the critical risky threshold.

To further reveal the possible coupling relationship between energy and cereals network, and its influence on global energy and cereals network. The coupling parameter between energy and cereals networks is proposed, and simulated in OLUCF. It can be found that under ULIS, while ULNL and LLNL is set as 0.3 and as 0.4 separately, the global energy and cereals networks has adequate potential to face the crisis of RUW, and the coupling parameter has nearly no influence on them.

Under LIULDS, the integrated energy and cereals network would have relative more reduction of the effective country nodes with consideration of the coupling process compared with the scenarios without consideration of the coupling process. The effective country nodes in the integrated energy network would reduce from 69.75 % to 56. 30% while the coupling parameter value is set as 0.40, and the effective country nodes in the integrated cereals network would reduce from 54.43 % to 51. 05% while the coupling parameter value is set as 0.40. The result indicates that although RUW has more significant influence on the cereals network than energy network, the coupling parameter would enhance more influence RUW on energy network than cereals network. The more important point is that, under LIULDS, along with the stronger coupling strength between the energy and food network, the easier to be destroyed by the specific disaster. The critical threshold is 0.05, it indicates that for the same country, if its node load in the energy or food network is lower than 0.05, then, the node in the other network would not be easily destroyed.

3.5. Network Robustness and Resilience

This study proposed a method to assess the network robustness and resilience characteristic against RUW under ULIS and LIULDS. Through observation of the bubble size of network in Fig. 5, it can be found that in the energy network, the integrated energy and oil network have the strong robustness against RUW, and in the food network, the cereals and barley network have the strong robustness against RUW. Through observation of NRE_d and NRE_{ind} value, it can be found that the coal, cereals and wheat networks have the strong ability of recover and anti-damage against RUW and global panic, while gas and maize network have relative strong recover ability and low anti-damage ability. Totally, all of the networks have relative consistent recover and anti-damage ability against RUW and the global panic except barley network. The barley network has low recover ability and anti-damage ability.

It can be also found that the there is no positive correlation between robustness and resilience. The strong robustness of barley network does not bring its strong resilience against RUW. It indicates that in the barley network, Russian and Ukraine have limited contribution to the global exports, and other main countries own the large ratio of global exports. The low robustness of coal network does not mean its low resilience ability. It indicates that Russian and Ukraine have dominant role in the global coal exports, however, the role can be easily replacement by other coal exports countries. For the network of the integrated energy and oil network, they have strong robustness, it indicates Russian and Ukraine have normal contribution to the global exports, at the same time, there are other countries with similar oil export scale that although they can not completely share the oil exports amount of Russian and Ukraine, they have the ability of anti-damage by RUW and the global panic. Fig. 6

3.6. Typical influence process of RUW

The typical influence process of RUW on the global energy and cereals network are assessed while the upper limitation of node load is set as 0.3 and the lower limitation of node load is set as 0.4 under ULIS and LIULDS. Under ULIS, there's no failure node in both of the energy and cereals network except Russian and Ukraine. The trade flow amounts have been changed a little, the total trade flow amount is reduced by 1.05%, in the energy network, while in the cereals network, the total trade flow amount is reduced by 0.71%. However, the influenced countries nodes in the energy network are more concentrated, while it is more disperse in the cereals network. The trade relationship edges have been reduced from 10260 to 9832 in the energy network, while in the cereals network, it has been reduced from 8528 to 8113. Through observation of the trade flow pattern, it can be found that there is some difference between energy network and cereals network. Without consideration the political relationship, it can be found that RUW would cause the significant reduction of energy trade flow from Russian to China, so as the flow to Korea Republic, Netherlands, Germany, Italy and Japan, while these influenced countries would search for replacement, such as the flow increment from Indonesia, Australia and Saudi Arabia to China, Norway to Germany, Canada to United States, Nigeria to Turkey, etc. RUW would cause the obvious cereals trade reduction from Russian and Ukraine to Egypt, Russian to Turkey and Saudi Arabia, and Ukraine to Spain, Netherlands, Indonesia, Turkey and Korea Republic. Then, these influenced countries would search for replacement such as France, Romania, United States and Australia to Egypt, United States and Canada to China, etc.

Considering the information of international relations order and geographical relationship, some more specific results we can obtain. The energy imports status of China may still maintain a normal level. The energy imports of Germany, Italy, Netherlands, Japan and Korea Republic would be vastly reduced. Especially, the long-term low-carbon energy transformation has decreased their dependency on the coal energy. At the same time, the clean energy ratio can not be increased in a short period, the limited land area in these countries has also restricted the potential of photovoltaic energy (Dupont et al., 2020). Therefore, there are three suggestions: Firstly, they should not only enhance the imports amount from the existed energy exports countries, the other newly energy trade relationship should be also established with other energy exports countries. Although, it would indicate higher transportation cost. For the countries themselves, they should further develop suitable new energy resources such as nuclear energy, wind energy, etc. They may even re-enable coal-based thermal power plant to deal with the urgent energy security crisis, even though it would induce short-term carbon emission increment. Secondly, the obvious suggestion is that other energy exports countries should enhance the ability of energy exports to deal with the global energy crisis. Lastly, the RUW does not indicate the absolute reduction of energy exports from Russian and Ukraine. The countries which have good relationship with Russian can

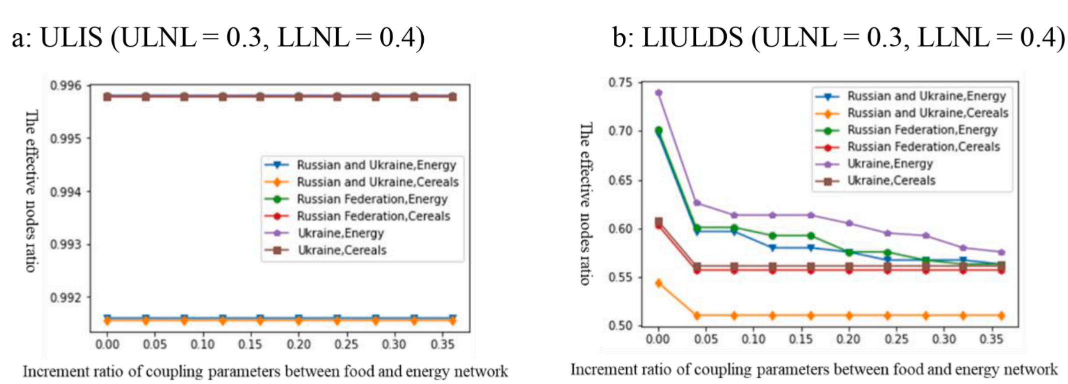

Fig. 5. Influence of RUW on coupled energy and cereals networks under ULIS and LIULDS

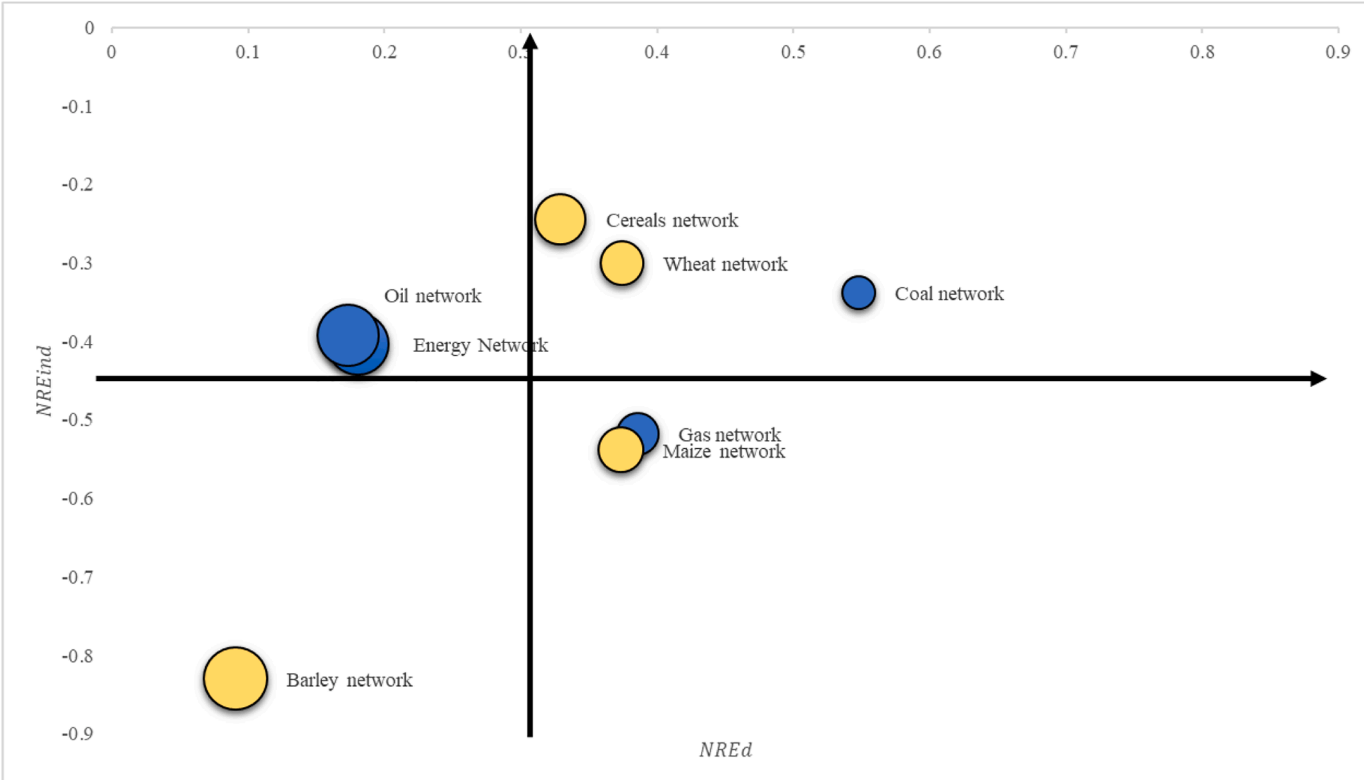

Fig. 6. Network Robustness and Resilience under ULIS and LIULDS. Note: the bubble size indicates the robustness strength of each network. The higher value of NRE_d and NRE_{ind} indicates the better resilience against RUW and the global panic. The black lines with arrow indicate the average value of NRE_d and NRE_{ind} of the eight networks.

support as transfer station for energy trade, such as China.

For the food security, the food imports of Egypt, Turkey, Saudi Arabia, Spain, Netherlands, Indonesia, and Korea Republic would be vastly reduced. Similarly, they should not only enhance the imports amount from the existed food exports countries, the other newly food trade relationship should be also established with other food exports countries. Although, it would indicate higher transportation cost. The other food exports countries should enhance the ability of food exports to deal with the global crisis.

Under the LIULDS with consideration the global panic, it can be found that, large ratio of countries nodes is destroyed or hurt, including 72 countries nodes in the energy network and 108 countries nodes in the cereals network. Most of the failure nodes are the little countries without adequate concentration in the current media such as Afghanistan, Pakistan, Algeria, Libya, Oman, Tunisia in the Africa and Central Asian. There are also 1644 edges in the energy network and 3211 edges in the cereals network are destroyed. The energy trade flow edges with large reduction include edges from Canada to United States, from Russian, Indonesia, and Saudi Arabia to China, from Australia to Japan, etc. The edges with large increment include edges from Canada to Japan, Nigeria to United States, Canada and Nigeria to China, and United States to Turkey. In the cereals network, the trade flow amount of the main edges including from Russian to Egypt and Turkey, United States to Mexico and Japan, Ukraine and Canada to China are reduced. The partial results are consistent with the influence judgement of RUW on the Egypt and Turkey from Lang et al (2022) Fig. 7.

A key phenomenon we should concern is that the largest trade flow amounts are not occurred in the failure nodes. The reason is that always the countries with large economic scale have more energy and food requirement, at the same time, they have more diversity of energy and cereals types and supply sources, and are more able to resist the risk of war. However, the failure nodes are always the countries with low economic scale and political status, they are unable to handle the risky caused by war, under the global panic, they do not have much more approaches to search for supply replacement of energy and cereals, and are more easily trapped in the crisis of energy and food shortages.

4. Conclusions

This study established an improved under-load cascading failure model, and can support for assessment of risky and influence process in the energy cereals network due to Russian and Ukraine War.

4.1. Policy implication

Based on the model simulation, we firstly can find that the importance of Russian and Ukraine on the global energy and cereals network. In the energy networks, the gas and coal trade networks are more significantly influenced by RUW than the oil network. In the cereals networks, RUW has more influence on wheat trade network. Totally, the cereals networks are more easily influenced by RUW than the energy networks.

Through scenario simulation, it can be found that the parameter of upper limitation of node load has the dominant function on the global energy and food security, while the influence of lower limitation parameter of node load has limited function. It reminds us that we should keep reserved capacity of energy and cereals as more as possible to resist the risk such as war, global warm and epidemic. We can also find that the integrated energy and cereals network has more robustness and resilience compared with the single type of network. The results tell us the energy substitution is an effective way to handle the risk of RUW. The more diversity of energy types was developed, the more able to survival in the risky world.

The lower limitation parameter of node load has limited influence on

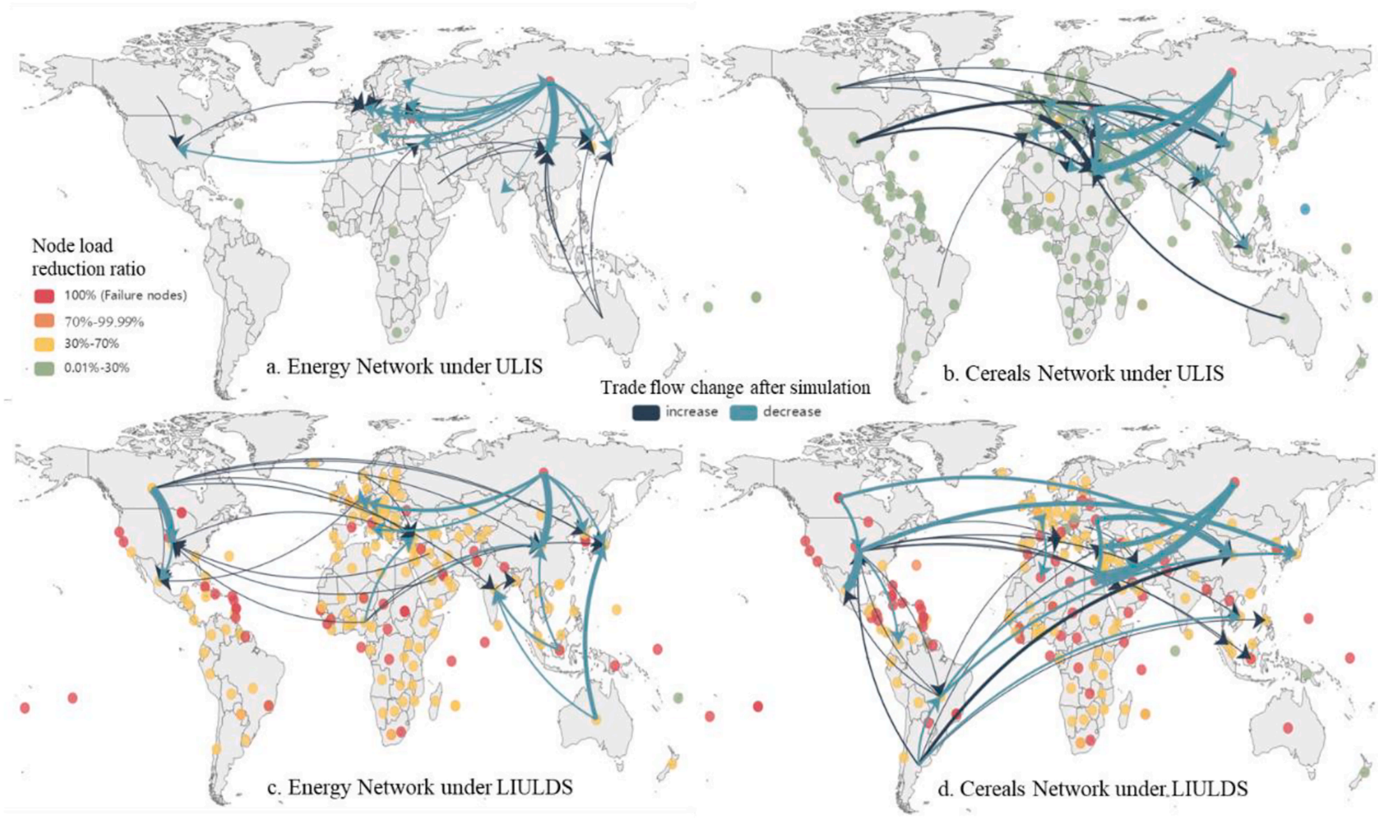

Fig. 7. Typical influence process of RUW under ULIS and LIULDS. Note: the trade flow change with the top 15 change amounts is presented including the increase amount and decrease amount respectively.

the global energy and cereals network with only consideration of the direct influence of RUW. However, if the global panic of energy and food shortages caused by RUW are assessed in the simulation, it would induce the global disasters. Even the integrated energy and cereals trade network can only maintain nearly 40. 75% and 54.43 of the effective countries' nodes. The results further strengthen the importance of enhance production ability and energy types to realize to resist the risk of RUW. The critical threshold of upper limitation and lower limitation of node load to protect global energy and food security is also obtained, totally we should try to maintain the export capability of the main exporting countries higher than 20 % to resist risky of RUW. With consideration of the global panic, we should try to maintain the export capability no less than 5%. The possible coupling relationship between energy and cereals network has limited influence on the global energy and cereals network with only consideration of the direct influence of RUW. Under LIULDS, the influence of the coupling effect on the energy and cereals network are amplified. What's more, the result indicates that although RUW has more significant influence on the cereals network than energy network, the coupling parameter would enhance more influence RUW on energy network than cereals network.

Through network characteristic comparison of robustness and resilience, it can be found that the coal, cereals and wheat networks have the strong ability of recover and anti-damage against RUW and global panic, while gas and maize network have relative strong recover ability and low anti-damage ability. Totally, all of the networks have relative consistent recover and anti-damage ability against RUW and the global panic except barley network. The barley network has low recover ability and anti-damage ability. There is no positive correlation between robustness and resilience. The strong robustness of barley network does not bring its strong resilience against RUW. It indicates that in the barley network, Russian and Ukraine have limited contribution to the global exports, and other main countries own the large ratio of global exports. The low robustness of coal network does not mean its low resilience ability. It indicates that Russian and Ukraine have dominant role in the global coal exports, however, the role can be easily replacement by other coal exports countries.

The detailed influence process of RUW on the global energy and cereal network can be also revealed through the OLUCF established in this study. The results tell us that RUW would induce global energy and food security crisis for all of the countries, the big countries with large economic scale would face relative obvious reduction crisis of energy and food supply, and the little and poor countries with small economic scale would be more easily collapsed. Therefore, the existed international energy and food security organizations should try to balance the global security demand between big countries and small countries to avoid the big countries to import and store too much energy and food that the other small countries are unable to maintain their energy and food security. Some new global powerful organizations can also be established to perform this function. We should pay more attention to the little and poor countries with small economic scale and low political status, which are the failure nodes in our mode simulation under LIULDS, especially the countries in the Africa and Asia to handle the risk. We should provide more energy and food supply for them.

4.2. Model applicability and limitation

The model established in this study can tell us the influence of RUW on the global energy and cereals networks quantificationally. The networks robustness and resilience against RUW can be also revealed based on the method of this study. The key weak points in the complex network and influence process can be also obtained under the specific circumstance. The model can also support for other events influence assessment, especially for the evaluation of material flow network such as energy, food, information, metals and other important materials.

There's still some deficiencies require improvement in the future research. First of all, in this study, the international relationships are not considered in the current research, the energy and food flow are determined based on the existed flow load, however, the political tendency would greatly change their decision. The influence factors of geography, politic and international relations order should be quantified and concerned in the future research (Theocharis and Jungherr., 2021). The related knowledge of computational communication studies and political communication sciences can be further introduced to observe the influence of theses factors on the energy and food networks. Then the robustness and resilience of the evolved network can be obtained based on the OLUCF. Secondly, in the influence assessment of RUW, we assumed that Russian and Ukraine are completely destroyed as the initial failure nodes, although the current results can provide us guidance to identify the global energy and cereals network weakness and risky. It possibly won't happen in fact, so it requires us to further assess the influence of RUW on exports ability of Russian and Ukraine. Only the direct relationship between imports and exports countries are considered in the current research. The intermediate nodes can be further considered that import energy and food from the initial destroyed countries and exports to other nodes. Lastly, to achieve more available results, the more scenarios can be set and simulated based on the key parameter combination of upper-limitation node, lower-limitation node, coupling effect with or without consideration the global panic of RUW.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Xi-Yin Zhou: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Gang Lu:** Writing – review & editing. **Zhicheng Xu:** Writing – review & editing. **Xiaoqing Yan:** Writing – review & editing. **Soon-Thiam Khu:** Conceptualization, Formal analysis. **Junfeng Yang:** Conceptualization, Formal analysis. **Jian Zhao:** Writing – review & editing, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data Availability

Data will be made available on request.

Acknowledgments

This research was supported by the National Key Research and Development Program of China (2021YFC3201505) and the Major Science and Technology Program for Water Pollution Control and Treatment (2017ZX07301-003).

References

Blanchard, O., Pisani-Ferry, J., 2022. Fiscal support and monetary vigilance: Economic policy implications of the Russia-Ukraine war for the European Union (No. PB22-5).
Benton, T., Froggatt, A., Wellesley, L., et al., 2022. The Ukraine war and threats to food and energy security.
Deng, M., Leippold, M., Wagner, A.F., Wang, Q., 2022. Stock Prices and the Russia-Ukraine War: Sanctions, Energy and ESG. Swiss Finance Institute Research Paper 22–29.
D'Odorico, P., Davis, K.F., Rosa, L., et al., 2018. The global food-energy-water nexus. Reviews of geophysics 56 (3), 456–531.
Duan, D., Lv, C., Si, S., Wang, Z., Boccaletti, S., 2019. Universal behavior of cascading failures in interdependent networks. Proceedings of the National Academy of Sciences 116 (45), 201904421.
Dupont, E., Koppelaar, R., Jeanmart, H., 2020. Global available solar energy under physical and energy return on investment constraints. Applied Energy 257, 113968.
Endo, A., Yamada, M., Miyashita, Y., et al., 2020. Dynamics of water–energy–food nexus methodology, methods, and tools. Current Opinion in Environmental Science & Health 13, 46–60.
Gaupp, F., 2020. Extreme events in a globalized food system. One Earth 2 (6), 518–521.
Guo, H., Zheng, C., Iu, H.H.C., Fernando, T., 2017. A critical review of cascading failure analysis and modeling of power system. Renewable and Sustainable Energy Reviews 80, 9–22.
Havlin, S., Kenett, D. Y., 2015. Cascading failures in interdependent economic networks. In Proceedings of the International Conference on Social Modeling and Simulation, plus Econophysics Colloquium 2014 (pp. 87-97). Springer, Cham.
Kruczkiewicz, A., Klopp, J., Fisher, J., Mason, S., Braneon, C., 2021. Compound risks and complex emergencies require new approaches to preparedness. Proceedings of the National Academy of Sciences 118 (19).
Lee, K.M., Goh, K.I., 2016. Strength of weak layers in cascading failures on multiplex networks: case of the international trade network. Scientific reports 6 (1), 1–9.
Liu, S., Yin, C., Chen, D., Lv, H., Zhang, Q., 2021. Cascading failure in multiple critical infrastructure interdependent networks of syncretic railway system. IEEE Transactions on Intelligent Transportation Systems.
Li, S., Li, L., Yang, Y., Luo, Q., 2012. Revealing the process of edge-based-attack cascading failures. Nonlinear Dynamics 69 (3), 837–845.
Lang, T., McKee, M., 2022. The reinvasion of Ukraine threatens global food supplies. bmj 376.
Mbah, R.E., Wasum, D.F., 2022. Russian-Ukraine 2022 War: A review of the economic impact of Russian-Ukraine crisis on the USA, UK, Canada, and Europe. Adv. Soc. Sci. Res. J 9, 144–153.
Mengoub, F. E., Dadush, U., Ali, A. A., Tsakok, I., 2022. The Russia-Ukraine War and Food Security in Morocco.
Meena, K.L., 2022. Impact of Russia Ukraine War on Indian Economy. Academic Journal of Digital Economics and Stability 16, 54–62.
Mammadov, E., 2022. The Economic Consequences of Russia-Ukraine War for Azerbaijan. Available at SSRN 4058963.
Oxford Analytica, 2022a. Russia-Ukraine war will impede China's economy. Emerald Expert Briefings (oxan-db).
Oxford Analytica, 2022b. Ukraine-Russia war will dent Japan's economy. Emerald Expert Briefings (oxan-db).
Osendarp, S., Verburg, G., Bhutta, Z., et al., 2022. Act now before Ukraine war plunges millions into malnutrition.
Ruhl, J.B., 2019. Governing Cascade Failures in Complex Social-Ecological-Technological Systems: Framing Context, Strategies, and Challenges. Vand. J. Ent. & Tech. L., 22, 407.
Ren, W., Wu, J., Zhang, X., Lai, R., Chen, L., 2018. A stochastic model of cascading failure dynamics in communication networks. IEEE Transactions on Circuits and Systems II: Express Briefs 65 (5), 632–636.
Tollefson, J., 2022. What the war in Ukraine means for energy, climate and food. Nature 604 (7905), 232–233.
Tiewsoh, L.S., Sivek, M., Jirásek, Jakub., 2017. Traditional energy resources in india (coal, crude oil, natural gas): a review. Energy Sources Part B Economics Planning & Policy 12 (2), 110–118.
Theocharis, Y., Jungherr, A., 2021. Computational social science and the study of political communication. Political Communication 38 (1), 1–22. -2.
Smolyak, A., Levy, O., Shekhtman, L., Havlin, S., 2018. Interdependent networks in Economics and Finance—A Physics approach. Physica A: Statistical Mechanics and its Applications 512, 612–619.
Shi, J., Zhang, C., Chen, W.Q., 2021. The expansion and shrinkage of the international trade network of plastic wastes affected by China's waste management policies. Sustain. Prod. Consum 25, 187–197.
Wang, X., Li, H., Yao, H., Zhu, D., Liu, N., 2018. Simulation analysis of the spread of a supply crisis based on the global natural graphite trade network. Resour. Pol. 59, 200–209.
Xing, L., 2020. Cascading failures in internet of things: review and perspectives on reliability and resilience. IEEE Internet of Things Journal 8 (1), 44–64.
Yang, Q., Scoglio, C.M., Gruenbacher, D.M., 2021. Robustness of supply chain networks against underload cascading failures. Physica A: Statistical Mechanics and its Applications 563, 125466.
Zhu, Y., Yan, J., Sun, Y., He, H., 2014. Revealing cascading failure vulnerability in power grids using risk-graph. IEEE Transactions on Parallel and Distributed Systems 25 (12), 3274–3284.
Zhao, J., Li, D., Sanhedrai, H., Cohen, R., Havlin, S., 2016. Spatio-temporal propagation of cascading overload failures in spatially embedded networks. Nature communications 7 (1), 1–6.
Żuk, P., Żuk, P., 2022. National energy security or acceleration of transition, Energy policy after the war in Ukraine. Joule 6 (4), 709–712.