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After the pandemic: the global seafood trade market forecasts in 2030

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The COVID-19 lockdowns have transitioned to a new normal and triggered commodity supply disruption and trade uncertainty, yet little is known about the seafood trade resilience of developing and developed countries amid pandemic-related shocks. Here, employing a newly developed geographical transition-net model, we simulate a set of idealized lockdown scenarios in a real-world seafood network. The results show that (1) even if restrictions from regions with high strictness policies were eventually lifted globally at the end of 2022, the pandemic-induced disruption will continue to affect global seafood trade until 2030, and the annual growth rate of the global seafood market would be around 1% lower than that during 2006–2019; (2) Due to the continued high level of stringency in China in 2022 and the soaring demand of seafood in the developed countries in the post-COVID-19 era, developed countries are increasingly reliant on their intra-regional trade until 2030; (3) The global seafood supply chains will magnify export losses beyond the direct effects of COVID-19, and there would be 17 to 57 million people in the developing countries in 2030 facing seafood supply shortage. The new long-term challenge is to call for the multilateral cooperation of major exporters for global seafood trade recovery. Our study provides a new perspective to evaluate the economic impact of COVID-19 as well as the cascading effect caused by the supply-chain linkages in the global seafood system.

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Introduction

The global seafood industry, being one of the most heavily traded food commodities, has exhibited lower resilience compared to other sectors within the agri-food industry in response to this crisis. For example, during the Coronavirus disease (COVID-19) pandemic crisis, both domestic and international food supply chains have been disrupted, resulting in the closure of food services, reduced transport services, and trade restrictions, among other challenges. The global seafood trade value experienced a significant decline of 14.8% according to a report by the United Nations Conference on Trade and Development (UNCTAD). In contrast, the global merchandise trade value only dropped by a lesser rate of 7.4% (FAO, 2020b; WTO, 2020; UNCOTAD, 2021). Meanwhile, considering that the global seafood market represents about 10% of all food trade (by value) and exceeds the combined value of sugar, maize, coffee, rice, and cocoa trade (John et al., 2015), its heavy reliance on international trade raises significant interest in understanding the impacts of the COVID-19 pandemic on the seafood trade network and supply chain (FAO, 2017; Herforth et al., 2020).

In addition, the ripple effects of the disrupted fish market supply chain continue to fall and will lead to an increased incidence of poverty crisis, especially in the fisheries in many developing nations. According to the World Wildlife Fund, the developing world employs 97% of the world's fishing workforce where 90% are small-scale fishermen, and about 200 million people are directly and indirectly employed along the value chain, many of whom are women. The developing countries in Asia, in particular, consist of 85% of the nearly 38 million full-time practitioners in global aquaculture value chains (Lungren et al., 2006; Egger et al., 2021), and over 23 million low-income population rely on small-scale fisheries (Blake et al., 2021). Exporting high volumes of seafood is one of the main sources of income in these developing countries. However, the demand outlook for seafood products during the pandemic has been brought to a halt or significantly reduced of seafood products in some countries of Asia (Islam and Shamsuddoha, 2018; Weersink et al., 2021). The decline in demand for seafood has led to fewer wage opportunities, while increased costs of transportation have led to either oversupply or wastage, leaving those in low-income groups vulnerable to poverty and malnutrition. The outlook of pandemic impacts is still overwhelmingly dominated by uncertainty, the global seafood market is thus calling for economic stimulus and plans for long-term changes in the seafood market landscape (Rathod et al., 2022).

The international community in 2015 adopted the 2030 Agenda for Sustainable Development, with the 14th Sustainable Development Goal (SDG) devoted for the first time to Oceans and Seas, which promotes the conservation and sustainable use of the oceans, seas, and marine resources (Virto, 2018; Lauritzen, 2021). This goal also links to zero hunger (2nd SDG) and sustainable consumption and production (12th SDG) goals. Nevertheless, achieving the trade-related targets of SDG14 requires the catalysis of new policies to restore the productive capacity of the seafood market and to increase economic benefits to developing countries (Garlock et al., 2019; FAO, 2020a; Sachs et al., 2021). While relatively few integrated studies exist that analyze possible response strategies of lockdowns contributing to mitigating seafood market losses (Love et al., 2021; Jones et al., 2022). Therefore, we respond to the urgent need for new analytical frameworks and scenarios that provide a basis for global seafood trade analysis, exploring how the possible lockdown restrictions strategies can keep the global seafood market stay within baseline by 2030, while at the same time ensuring economic balance for developing countries.

We firstly optimized a Geographical Petrinet (Geo-PN)(Ge, Xing and Cheng, 2010) model to construct the cascading relationships of the global seafood supply chain across 21 regions based on the FAO's seafood trade classification (Supplement Fig. S1a). Given that the lockdown measures can be represented by the degree of labor and transport availability, we then developed a specific Stringency Index (SI) on the basis Coronavirus Government Response Tracker (OxCGRT) (Hale et al., 2021) (see Table S1 in Supplement) to represent the restriction policy of global 21 regions for COVID-19 in 65 different lockdown restrictions scenarios. Finally, we grouped the 21 regions into 9 groups, which represent the Top 5 import/export regions, and other developing and Other developed regions according to the World Bank's income classification (Supplement Fig. S1b). These classifications help with analyzing seafood trade among countries with different concentrations of seafood productivity and levels of economic development. On the basis of this framework, we explore the incidence of seafood trade damages in developing countries, in order to inform the allocation of international collaboration and economic stimulus corresponding to ongoing pandemic shock.

The benefits of the Geo-PN model are two-fold. First, distinct from the empirical steady-state networks studies, the optimized Geo-PN model incorporates the historical knowledge of economic impacts with the self-adaptive system of the global seafood trade network (More details in Fig. 1 in Methods), which contributes to a more realistic representation of how negative shocks propagate through supply chains. Second, it enables the representation of the spatial trajectories of cascading effects across different regions throughout complex global supply chains. The size and persistence of shock propagation of different regions shown in the Geo-PN model enable us to depict their system resilience within the seafood trade network (Gephart et al., 2016; Fair, Bauch and Anand, 2017; Huang et al., 2020). The goal of this study is not to predict the actual cost of the COVID-19 pandemic in the global seafood trade, but to analyze the cascading effects of shock on the seafood market more accurately. Identifying the regional resilience of the seafood supply system amid pandemic shocks can provide useful insights into tailoring different trade stringency strategies for future pandemic crises.

Methods

Empirical network formation models focus on either describing different network formations or detecting the clusters and communities. These models utilize the commodity (e.g. agri-food, wheat, seafood, etc.) network parameters, such as degree centrality, closeness centrality or eigenvector centrality, etc., to unravel the multifaceted, uneven, and often contested dimensions of globalization (Costello et al., 2020; Suh and Pomeroy, 2020; Stoll et al., 2021). However, these approaches normally treat the food trade networks as a static or single-year "snapshot" and neglect the economic cascading effect from one region to other regions within the network, potentially leading to a partial understanding of the actual economic loss (Belton et al., 2020). Macro-scale economic cascading simulation models, such as the Adaptive Regional Input-Output (ARIO) model (Watson et al., 2017) and the Computable General Equilibrium (CGE) model (Shan et al., 2020), were proposed to demonstrate the linear and nonlinear input-output relationships and assess the economic consequences of disastrous events. Different from these macro-scale economic cascading simulation models, the Geo-PN model has the advantage of simulating the dynamics of network transition forms at different aggregated scales to capture their economic cascading effect as well as their spatial trajectories behind the seafood supply-chain linkages (Ge et al., 2010; Koks et al.,

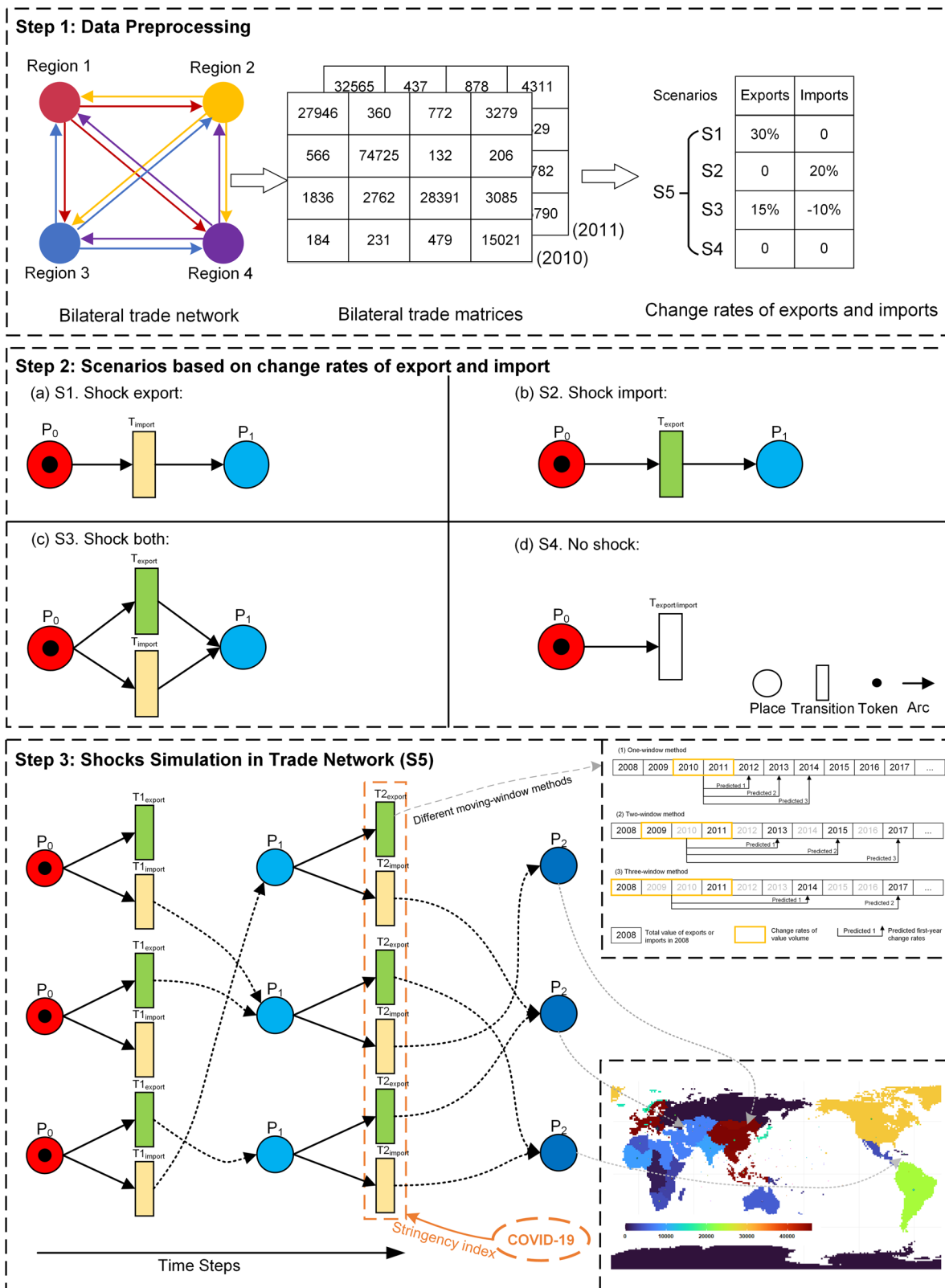


Fig. 1 The workflow of the Geo-PN model. The dynamic simulation graph can be found in the supplement.

2016). It means that the Geo-PN model is more flexible in delineating the microscale of the cascading effect behind the intricate linkages among sectors in the global seafood system, and the spatial trajectory of the cascading effect from one sector to another in the Geo-PN model can be simulated near real-time.

This paper took the real lockdown restriction strategies in 2020 as a starting point for a set of future scenarios' simulations. Given that the lockdown measures can be represented by the degree of labor and transport availability, we developed specific SI on the basis of the Coronavirus Government Response Tracker

(OxCGRT) (Table S1 in Supplement) to represent the restriction policy of the 21 regions for COVID-19 in 65 scenarios. Each of the 65 scenarios was based on a different combination of geographical scale, duration, and strictness of national lockdown restrictions. These 65 response strategies provide a unique integrated overview of possible collaboration paths, including: (1) shifting towards less trade-losses lockdown strategies, and (2) increasing seafood trade efficiency during the pandemic.

With respect to the overview of the methodology of our work (Fig. 1), we first constructed multiple years of bilateral trade matrixes to estimate the change rates of exports and imports, then we simulated four types of basic cascading passes based on Geo-PN model, i.e., only shock export or import, shock both of export and import, and without any shocks, to represent the cascading processes of global seafood network. To better demonstrate the spatial-temporal variations within the global network, different moving windows were selected in the simulation models. In the validation part, our optimized Geo-PN model was validated with the 2008–2011 financial crisis and then was used to predict the Asian seafood trade's reaction to COVID-19, as well as its potential forward propagation to the global seafood trade network in 2030. The SI was introduced to represent the shocks of COVID-19 and compare it to the case without it.

The construction of interdependencies. In this study, we used the trade integration index (TII) which was proposed by the economist Brown A.J. (Brown, 1949), to measure the degree of trade interdependence between two countries. A higher value indicates closer trade links between the two countries, and its equation of TII is shown as follows:

$$TII_{i,j} = \frac{X_{i,j}/X_i}{M_j/M_w} \quad (1)$$

where i, j, w represent two countries (regions) and the world market; TII_{ij} refers to the trade integration index of i and j ; X_{ij} represents the export values of country i to country j ; X_i denotes the total export values of country i ; M_j represents the total import values of a country j . $TII_{ij} > 1$ indicates that i and j have a close trade relationship; $TII_{ij} < 1$ shows that the trade relationship between i and j is weak. Therefore, we set the threshold to 1 to determine whether the cascade effects can continue to the next node.

Geo-PN simulation. The Geo-Petri Net model, proposed by Ge et al. (Ge et al., 2010), was applied in this study to capture the cascading effect within the global seafood network after a financial crisis or COVID-19 pandemic. A Geo-PN is a five-tuple as follows:

$$GeoPN = \{P, E, I, O, S\} \quad (2)$$

where $P = \{\dots, p_i, \dots\}$ is the set of probabilities of cascading failure for regions, which is set to be shocked initially; $E = \{\dots, e_{ij}, \dots\}$ is the set of strength of relations between regions; I is the set of parent nodes; O is the set of child nodes; $S_{\text{export}} = \{\dots, s_{i,\text{export}}, \dots\}$ and $S_{\text{import}} = \{\dots, s_{i,\text{import}}, \dots\}$ is the set of states of export and import for regions, respectively. Unlike previous studies, here we introduced the concept of probabilities for S . For example, $s_{i,\text{export}} = 0.2$ means the export of region i is shocked by 20%, and $s_{i,\text{export}} = 0$ means the export of region j is in a normal state (unshocked).

The principle of Geo-PN is that the shock of export (or import) for parent nodes will bring import (or export) impacts to child nodes. For example, the imports of region i had a 20% shock, which may result in cascading effects of exports to other regions on different levels. Therefore, different probabilities were

generated in the Geo-PN model for the export and import of each region under the same shock, and the child nodes were randomly selected according to probabilities in the cascading process. Figure S7 shows the details of the cascading process of the Geo-PN model based on the financial crisis in 2008–2011. For the state of shock probabilities, the defined threshold $\lambda = 1$ from TII was selected to judge the state of each region. If N_0 denotes the set of regions in shock for exports, $i \in N_0$, then the successful transmission probability (when $p_i \times TII_{ij} > \lambda$) for imports p_j from i to j in an iteration is as follows:

$$p_j = \frac{TII_{ij} \times p_i}{\sum_{j=1}^n TII_{ij}} \quad (3)$$

where TII_{ij} is the TII (as interdependency) between region i and j , p_i is the initial shock probability for region i . The hidden risk $R = p_i \times TII_{ij}$ ($R < \lambda$) can record the case where the cascading pass did not succeed. The TII and trade network matrices were updated after each cascade was complete, the shocks of imports or exports of region j were ultimately reflected in the reduction of total values of imports or exports respectively. In addition, we can track the transmission path of cascading effects from regions in failure to others.

For each region in a cascading process, there are parent and child regions I and O that transmit and receive impacts, respectively. We simulated 500 random events, and each event contained more than 450 time steps. In each event, the next step sub-event depends on the result of the previous step. For each step length, affected regions were cascaded sequentially, the loop was completed when the times of iterations were reached in the simulation of a specific sub-event.

Validation and prediction. The selections of moving windows influence the TII index at each Geo-PN simulation procedure. In this study, three types of moving windows, including 2010–2011, 2009–2011, and 2008–2011 years of TII were selected to test the Geo-PN simulations under the 2009–2011 financial crises (Fig. S8). The mean error (ME) and root mean square error (RMSE) were used to evaluate the simulated accuracy, as well as the variances of iterations across different moving windows were the optimal iteration required from the window years to prediction years for each method. Finally, the optimal moving window, as well as the iterations were combined with Geo-PN to predict the trade values and the global network trajectory under 65 potential scenarios and adjusted scenarios (Tables 1 and 2) in 2030. In this step, the prediction model was simulated at two scenarios: with and without the consistent impact of COVID-19 using the stringency index.

Results and discussion

The 2030 global seafood trade volume is still expected an increase in response to the pandemic shock. Compared to our Geo-PN model, the global seafood trade in our project is estimated to grow by 4.08% from 2021 to 2023 under the without-pandemic scenarios. This growth rate is slightly lower than the annual growth rate of over 5.3% predicted by the Organization for Economic Co-operation and Development and the Food and Agricultural Organization (OECD-FAO). The disparity can be attributed to a statistical difference of around 2 million metric tons (MT) in global seafood trades between the OECD-FAO (OECD-FAO, 2020) and FAO statistics. The OECD-FAO model relies more heavily on FAO data, which primarily represents food fish consumption and meal inputs, whereas the global seafood trade encompasses a broader range of products beyond fishmeal-related ones. This discrepancy accounts for the differences in

Table 1 Settings of the 65 scenarios.

Strictness	S1 ¹	S2 ²	S3 ³	S4 ⁴	S5 ⁵	S6 ⁶	S7 ⁷	S8 ⁸	S9 ⁹
1	Real SI in 2020	S2-20	S3-20	S4-20	S5-20	S6-20	S7-20	S8-20	S9-20
2		S2-40	S3-40	S4-40	S5-40	S6-40	S7-40	S8-40	S9-40
3		S2-60	S3-60	S4-60	S5-60	S6-60	S7-60	S8-60	S9-60
4		S2-80	S3-80	S4-80	S5-80	S6-80	S7-80	S8-80	S9-80

¹ Represents the real SI scenario in 2020;
² Represents that all the developed regions change their strictness from 20 to 80 together;
³ Represents all the developing regions change their strictness from 20 to 80 together;
⁴ Represents Top 5 export regions change their strictness from 20 to 80 separately;
⁵ Represents Top 5 export regions change their strictness from 20 to 80 together;
⁶ Represents Top 5 import regions change their strictness from 20 to 80 separately;
⁷ Represents Top export regions change their strictness from 20 to 80 together;
⁸ Represents global net export regions change their strictness from 20 to 80 together;
⁹ Represents global net import regions change their strictness from 20 to 80 together.

Table 2 Adjusted Scenario-sets.

Strictness	AS1 ¹	AS2 ²	AS3 ³	AS4 ⁴	AS5 ⁵	AS6 ⁶	AS7 ⁷	AS8 ⁸	AS9 ⁹
1	Real SI in 2022	AS2-20	AS3-20	AS4-20	AS5-20	AS6-20	AS7-20	AS8-20	AS9-20
2		AS2-40	AS3-40	AS4-40	AS5-40	AS6-40	AS7-40	AS8-40	AS9-40
3		AS2-60	AS3-60	AS4-60	AS5-60	AS6-60	AS7-60	AS8-60	AS9-60

¹ Represents the Real SI scenario in 2022;
² Represents that all the Top 5 exporters of developing regions change their strictness from 20 to 60 together when the SI of the developed regions decreased to 0; 2 represents Top 5 importers of developing regions change their strictness from 20 to 60 together;
³ Represents Top 5 importers of developing regions change their strictness from 20 to 60 together;
⁴ Represent Top 5 importers of developing regions change their strictness from 20 to 60 together;
⁵ Represents Top 5 importers of developing regions change their strictness from 20 to 60 together;
⁶ Represents Top 10 exporters of developing regions change their strictness from 20 to 60 together;
⁷ Represents Top 10 importers of developing regions change their strictness from 20 to 60 together;
⁸ Represents global top 10 exporters regions change their strictness from 20 to 60 together;
⁹ Represents global top 10 importers regions change their strictness from 20 to 60 together.

predictions between the two models (Model evaluation can be found in Fig. S6 in the supplement).

Our analysis (Fig. 2a) reveals that even in the face of COVID-19, the global seafood trade volume is projected to exhibit an annual growth rate of 2.88% under the with-pandemic scenario. This suggests a 24.91% increase in the next decades, slightly lower than the 28.94% increase observed in the previous decades. In comparison, the OECD-FAO predicts a 5.3% increase in world exports of food fish over the next decade (OECD-FAO, 2020), considering the impact of the pandemic. While our projections differ slightly from the OECD-FAO prediction, they still indicate a faster recovery in seafood trade than initially anticipated.

As one of the most-traded food categories globally, our findings underscore the expected growth in global seafood trade. This growth is influenced by factors such as the impact of the pandemic, regional statistical variations, and evolving dietary preferences. Notably, our results align with Bennett’s Law, which describes the contrasting patterns of food consumption observed across different countries (Hale et al., 2021). The increasing demand for seafood protein is driven by population growth, and dietary transformations in developing nations due to rising incomes and urbanization.

Based on the growth trends observed in different regions (Fig. 2b), it is evident that the future potential for seafood exports lies predominantly in developing regions, particularly South Asia, Southern Africa, Central America, and Oceania’s developing regions are also expected to continue growing and occupy a larger share in global export regions. Between 2006 and 2019, the majority of aquaculture production came from China, East and Southeastern Asia, and Southern Africa and the seafood system has transitioned from capture fisheries to an aquatic food system, these regions still face limitations in terms of horizontal expansion of pond areas and achieving higher productivity per

unit area, as outlined in the Life Cycle Theory (Hu et al., 2020). Consequently, Central America, South Asia, and Southern Africa are gradually developing their aquatic systems and are likely to replace the current leaders in the next decade. However, it’s important to note that apart from the challenges posed by the pandemic, the global seafood system will also face threats such as freshwater depletion, land use and land-use change, biotic resource use, biodiversity loss, and disruptions in global phosphorus and nitrogen cycles (Gordon et al., 2017). These factors may limit the development of aquaculture products in the near future.

Developed countries (mainly the Western Europe and European Union) are increasingly reliant on the own intra-regional trade in response to the pandemic shock

Sankey diagrams (Fig. 3) provide a visual representation of the complex interconnections and resource flows within the seafood trade, allowing for an understanding of the varied impact of COVID-19 on seafood supply across regions.

As shown in Fig. 3b, it becomes evident that the pandemic shock will impede global seafood exports from developing countries and also hinder intra-regional trade within these regions. In more detail, although developing countries will continue to play a significant role in seafood exports, accounting for over 58% of the exported seafood goods under the with-pandemic scenario. While this proportion is approximately 2% lower than the without-pandemic scenario. Meanwhile, the decrease in regional trade between developing countries is more pronounced (25.11%) compared to that between developing and developed countries when analyzing the scenarios of a world with and without the pandemic in 2030.

By contrast, our findings indicate that the low level of self-sufficiency in developed countries, coupled with their increased

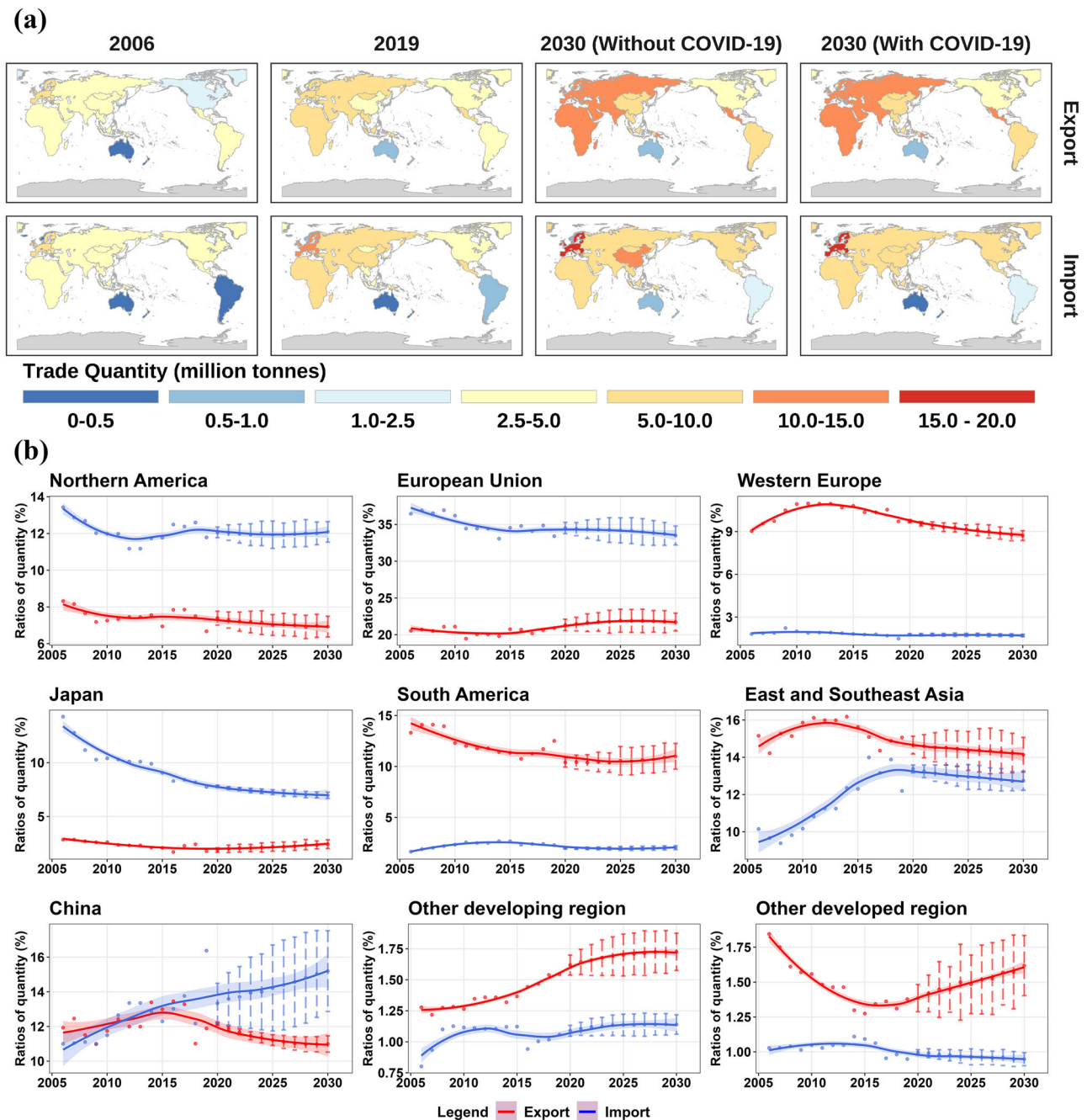


Fig. 2 Visualizing the evolution and projections of global seafood trade quantities. **a** The historical seafood trade quantity (million tonnes) in global 9 regions over the period of 2006 to 2019 and the simulated seafood trade quantity under the with- and without-pandemic scenarios in 2030; **b** The ratio of seafood trade quantity in global 9 regions over the period of 2006 and 2030, the error bar demonstrates the uncertainty of simulation results under 65 scenarios. The historical raw data are from the FAO.

seafood demand in the post-COVID-19 era, has led to a shift towards greater reliance on intra-regional trade. In the historical fish export market, developed countries have traditionally been the primary exporters to developing countries. However, in 2030, under the with-pandemic scenario (Fig. 3b), 29.75% of seafood will be imported from developed countries, surpassing the import levels of 2019.

The outcomes of developed countries are increasingly reliant on their own intra-regional trade aligns with the theory proposed by Paul Krugman, known as the New Economic Geography (NEG) (Fujita and Krugman, 2004). NEG provides an explanation for trade patterns between developed countries (North-

North trade) and developing countries (South-South trade). In the context of North-North trade, Krugman's theory suggests that advanced economies engage in trade with each other primarily due to economies of scale (Krugman, 1984). In the seafood trade market, economies of scale can arise from strict regulations and standards for food safety and quality in developed countries' seafood production. Additionally, developed countries often have better access to advanced technology and innovation, improving fishing and aquaculture practices and enabling efficient cold chain management (Asche et al., 2018). Furthermore, they possess well-established trade agreements and global market access, facilitating the export of seafood products to both developed and emerging

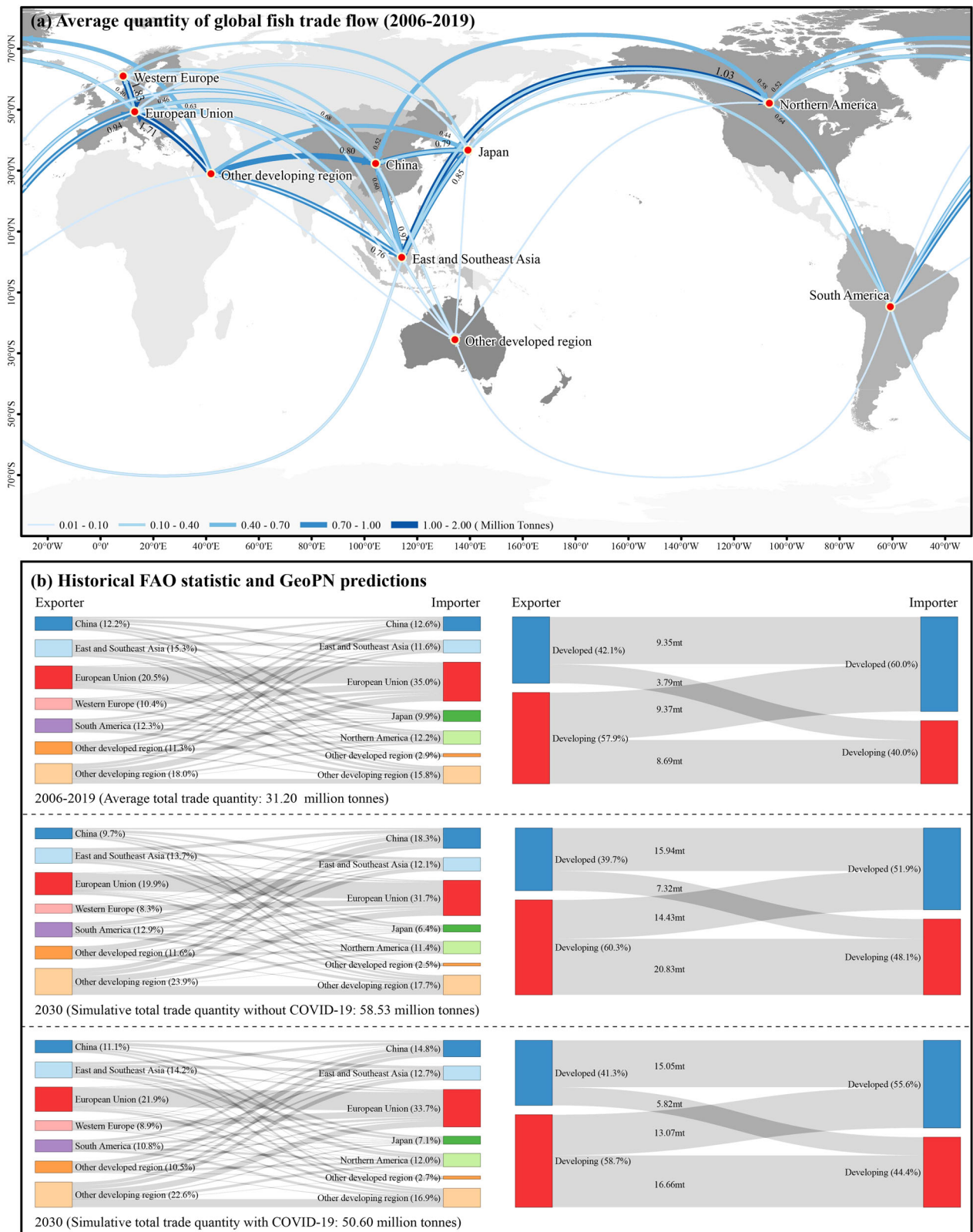


Fig. 3 Mapping the past and forecasting the future of global seafood trade flows. **a** The seafood trade flows (MT) between Top5 import/export and Other developed/developing regions over the period of 2006 to 2019. The arc length of an outer circle indicates the sum of food exported and imported in each group; **b** The Sankey diagrams of the historical global seafood trade network (2006–2019) and the simulated network under the with- and without-pandemic scenarios in 2030. The inner gray lines refer to the quantity of seafood from exporters to importers. The historical raw data are from the FAO.

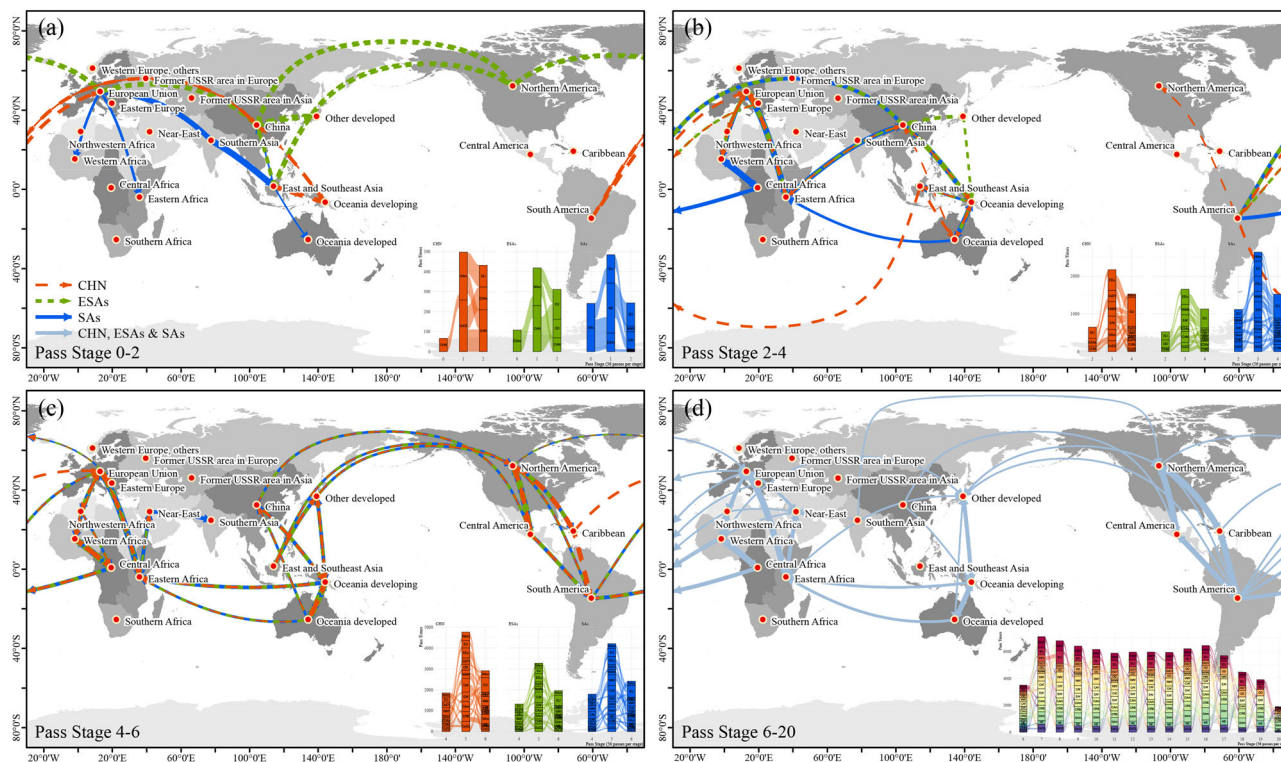


Fig. 4 Different stages of cascading trajectories of Geo-PN-based Global seafood simulations in 2030 under the COVID-19 pandemic crisis shock. **a** In the initial two cascading stages, the pandemic shock originated in China and subsequently propagated to the Oceania developing region, Africa, and East and Southeastern Asia. These regions, in turn, initiated cascades of the shock towards Europe and North America; **b** In the second round of cascading stages South America began experiencing the influence of the pandemic shock. **c** In the third round of the cascading stage, the cascading trajectory started to repeat, and all countries faced multiple impacts; **d** In the fourth round of the cascading stage, the cascading effect intensified and repeated across all regions, indicating a widespread and sustained influence of the pandemic shock.

markets (Esty and Geradin, 1997; Ahmed, 2005). These factors provide seafood exporters with expanded opportunities for market diversification and growth. Krugman also argues that advanced economies, with their larger markets, achieve economies of scale and produce goods at lower costs (Tumwebaze and Ijjo, 2015; Wahidin and Purnhagen, 2018). Thus, it is advanced technologies rather than natural resources that drive the increase in intra-regional trade in developed countries.

Developing countries face greater economic resilience challenges compared to developed countries when it comes to the propagation of shocks in the global seafood trade

To comprehensively analyze the uncertainty and potential impact of the post-pandemic situation, we performed a thorough assessment using 65 unique combinations of SI values, spanning from 20 to 80% (for more details, refer to Table 1 and Tables S1–S2 in the methods section). Our objective was to illustrate the resilience of various regions by drawing upon the concept of supply-chain resilience. We introduce the concept of global seafood trade resilience (Macdonald et al., 2018), which measures a country’s capacity to withstand disruptions to international trade (*trade uncertainty*) and recover after such disruptions (*responsiveness in propagating shocks*). To quantify this resilience, we employed two key indicators in the Geo-PN models: the number of cascading trajectories observed in each region within the global seafood simulations (representing the responsiveness in propagating shocks) (Fig. 4), and the seafood import and export trade uncertainty observed across the 65 cascading simulation scenarios (representing the trade uncertainty) (Fig. 5).

In terms of trade uncertainty, developing countries face greater uncertainty in seafood trade compared to developed countries. As

depicted in Fig. 5, among the 65 scenarios, the overall global seafood export exhibits a general increasing trend compared to 2019. However, the trade volume still faces a range of uncertainties, with potential reductions ranging from 1.23 to 26.85%. Furthermore, the proportion of export losses in developing countries (14.05%) is approximately 1.8 times higher than that in developed countries (7.82%). Similarly, the potential reduction in the proportion of import losses in developing countries is roughly 2 times higher than that in developed countries (Fig. 3a and Fig. S5).

Regarding the responsiveness in propagating shocks, we anticipate that significant global shocks can be mitigated within 3 years (Fig. 6a-threshold = 10), while shocks at the median level may take up to 8 years to retreat (Fig. 6a-threshold = 5). However, small cascading effects are expected to persist until 2028 (Fig. 6a-threshold = 1). Additionally, cumulative results indicate that regions with lower development levels are more likely to experience long-term propagation persistence (Fig. 6b). For example, since 2020, the European Union has demonstrated remarkable adaptability in its import patterns. Although it experienced high-level propagating shocks (cascading procedures >200 times), it is projected to recover within approximately 2 years, transitioning to median and low levels of impact. Similarly, Developed regions such as Northern America, Western Europe, and Japan faced significant influences on their imports at the first time, but their recovery period is comparatively shorter, estimated to be around 4 years. In contrast, South America and other developed regions are expected to require a longer time to recover.

It is noteworthy that China, along with East and Southeast Asia, stands as an exception. Despite a substantial decrease in the

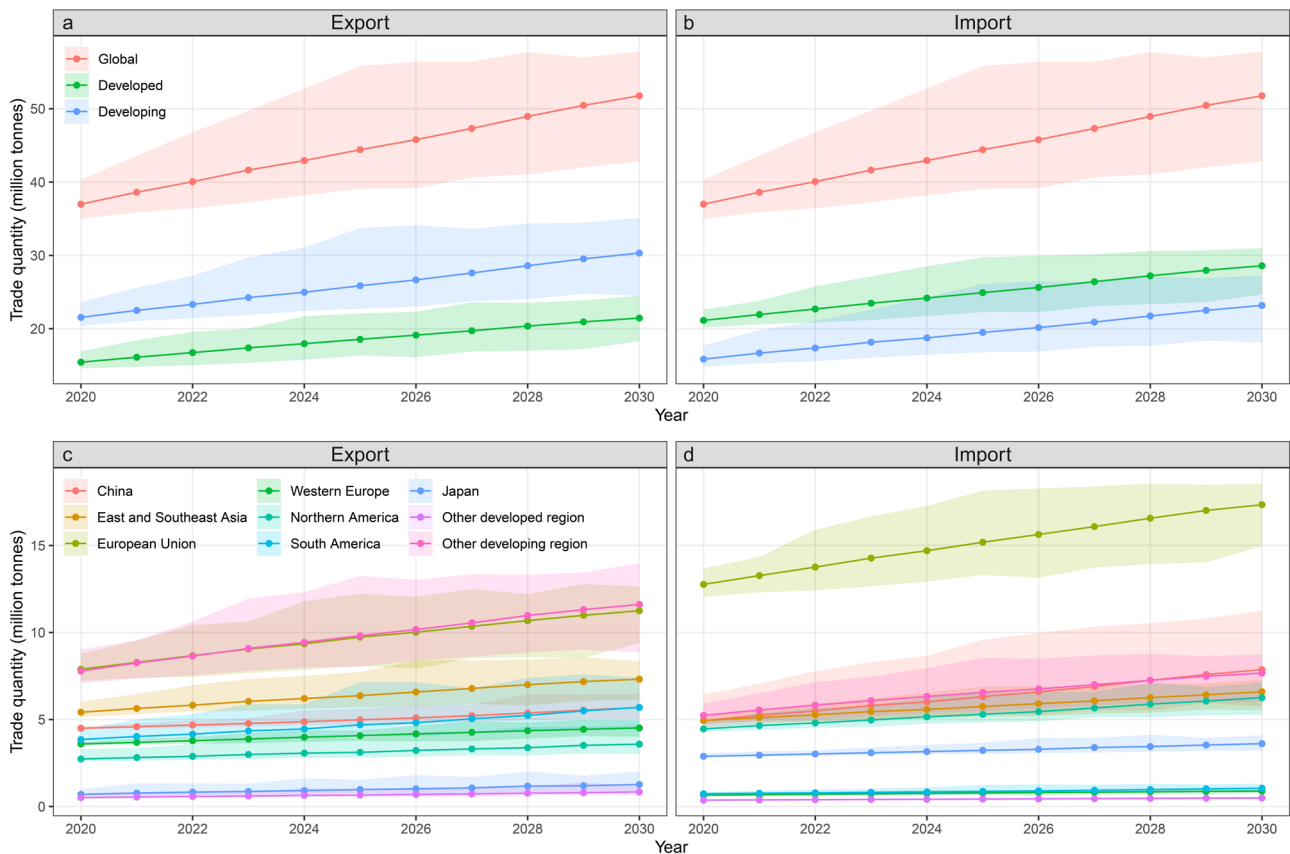


Fig. 5 Assessing baseline and uncertainty in simulated seafood trade across various scenarios and scales. **a** The baseline and the uncertainty of simulated seafood export at a global scale, developed regions and the developing regions, respectively under 65 scenarios. **b** The baseline and the uncertainty of simulated seafood import at a global scale, developed regions and developing regions, respectively under 65 scenarios; **c** The baseline and the uncertainty of simulated seafood export across 9 groups under 65 scenarios; **d** The baseline and the uncertainty of simulated seafood import across 9 groups under 65 scenarios.

cascading effect on their imports, these regions continue to experience a persistently high level of propagating shocks, with more than 150 times of the cascading procedures in the next decade. Meanwhile, the export cascading effects in these two regions also tend to gradually intensify, surpassing the impact levels observed in developed countries, which have fewer than 150 times of cascading procedures.

Hence, the COVID-19 pandemic, characterized by low probability and high-impact systemic risk, severely disrupted international trade and is projected to intensify trade tensions, exacerbating economic disruptions. Among the 21 countries analyzed, those within the European Union, Japan, and Northern America have a higher level of trade interdependence with network relationships exceeding 19. This level of interdependence surpasses that of developing countries. These regions have developed increasingly diversified trade networks, incorporating alternative sources and routes. This strategic approach enables them to mitigate the impact of external shocks on trade and transportation costs, enhancing their resilience in the face of disruptions. These findings align with the role of diversification in strengthening resilience, as stated by Borbor et al. (2019).

Policy actions need to be carried out to support multilateral cooperation for the global seafood trade recovery

The aforementioned findings indicate that developing countries are more vulnerable than developed countries during the COVID-19 pandemic. Specifically, the decrease in seafood

exports in regions such as East Asia-Pacific, Latin America and the Caribbean, North Africa, and the Near East will lead to food insecurity and hinder the ability of these countries, which heavily rely on seafood, to meet their nutrition targets. Consequently, it is essential to develop various recovery scenarios from the COVID-19 pandemic, with a specific focus on the recovery plans for developing countries. In light of this, we considered the SI in 2022 as a benchmark for each country’s strictness policy, which represents a "new normal" scenario (refer to Table S3 for specific details). Then we utilized the SI in 2022 to design 10 "recurrent with global cooperation" scenarios, referred to as Adjusted Scenario-sets (Table 2) (AS), aimed at exploring potential solutions for the recovery of global seafood trade (refer to Table 1 and Table S3 in the supplement for further information).

Our results indicated that to accelerate the global seafood market recovery and decrease the seafood trade inequalities in developing countries, the Top5 exporters of developing countries should work together and decrease their SI to at least 20 in 2022 to ensure global seafood trade growth by 2030. For instance, if only the SI of developed countries is adjusted (e.g., AS9-60 SI in Fig. 7), the improvement of other developing countries is limited (<2%), and the global seafood export still faces around 1% reduction. While if both China and East-Southeast Asia actively participate in the adjustment of SI and reduce their SI lower than 40 (e.g., AS2-20 and AS10-20 in Fig. 7 and AS4-40 and AS7-40 scenarios in Fig. S5), the other developing countries can achieve around 10% of growth, and global seafood export would expand by 1%. All the AS1-AS9 adjusted scenarios lead to a general

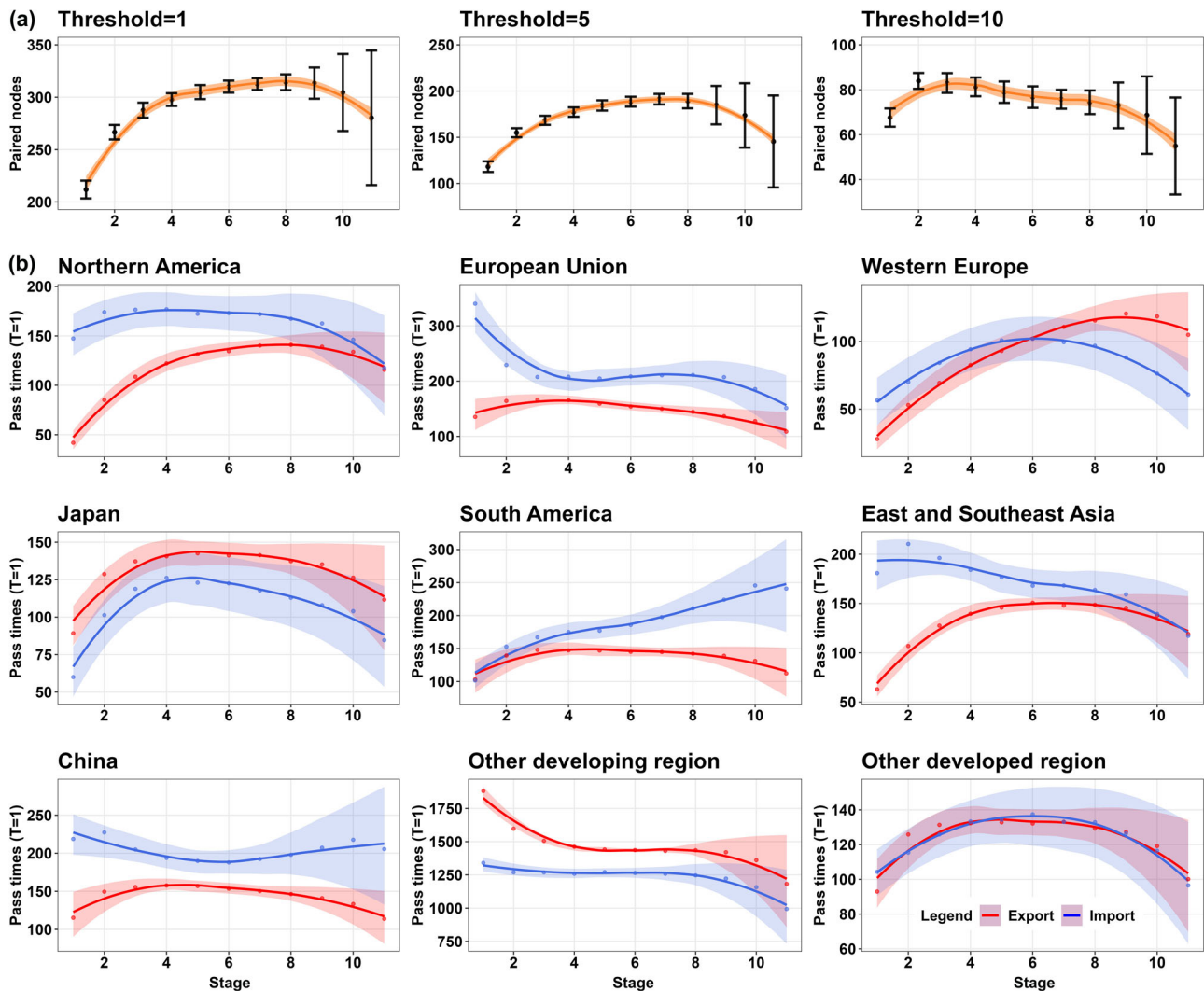


Fig. 6 The resilience of the global seafood network in the pandemic propagating shocks. **a** the overall responsiveness of the whole global seafood network across the 65 global seafood simulations, x-axis represents the years from 2023 to 2030, y-axis represents the number of cascading trajectories observed at three levels; **b** the responsiveness of import and export trade in 9 regions across the 65 global seafood simulations, x-axis represents the years from 2023 to 2030, y-axis represents the number of cascading trajectories observed from import and export trades.

insight—only relaxing lockdown restrictions in developed countries cannot reduce the global seafood trade-losses in the near future, and actions from China and East-Southeast Asia are needed to support multilateral cooperation on crisis response, resilience in seafood market (Details in Fig. S5).

Conclusions and policy recommendations

Concluding remarks. The Geo-PN model maps out the global seafood network’s reaction in the next 10 years of the pandemic and provides evidence of a self-adjustment in the seafood system under the scenarios where the supply for regional seafood spikes abruptly. The key conclusions drawn from this analysis are as follows:

1. Despite the pandemic shocks leading to a significantly lower projected annual growth rate of the global seafood market, around 2.88% by 2030, the rapid population growth and increasing aquaculture practices in developing countries are expected to drive global seafood demand. This phenomenon aligns with Bennett’s Law (Bennett, 1941), which refers to the international contrasts in food consumption based on varying socioeconomic factors.

2. In the post-pandemic era, developed countries will increasingly rely on intra-regional trade as a response to the shocks. Their advanced technology, innovation, well-established trade agreements, and access to global markets enable efficient cold chain management and facilitate intra-regional trade. This finding aligns with the s theory of advanced economics proposed by Paul Krugma (Krugman, 1984; Fujita and Krugman, 2004), which explained the trends and spatial patterns of North-North trade.
3. Among the 21 countries analyzed, those within the European Union, Japan, and Northern America exhibit a higher level of trade interdependence compared to developing countries. These regions have developed increasingly diversified trade networks, enabling them to mitigate the impact of external shocks on trade and transportation costs in the face of disruptions. These findings align with the role of diversification in strengthening resilience, as stated by Borbor et al. (2019).
4. The simulation model indicates that relaxing lockdown restrictions in developed countries alone will not be sufficient to reduce global seafood trade-losses in the near future. It emphasizes the need for intra-regional collaboration and multilateral cooperation, particularly among

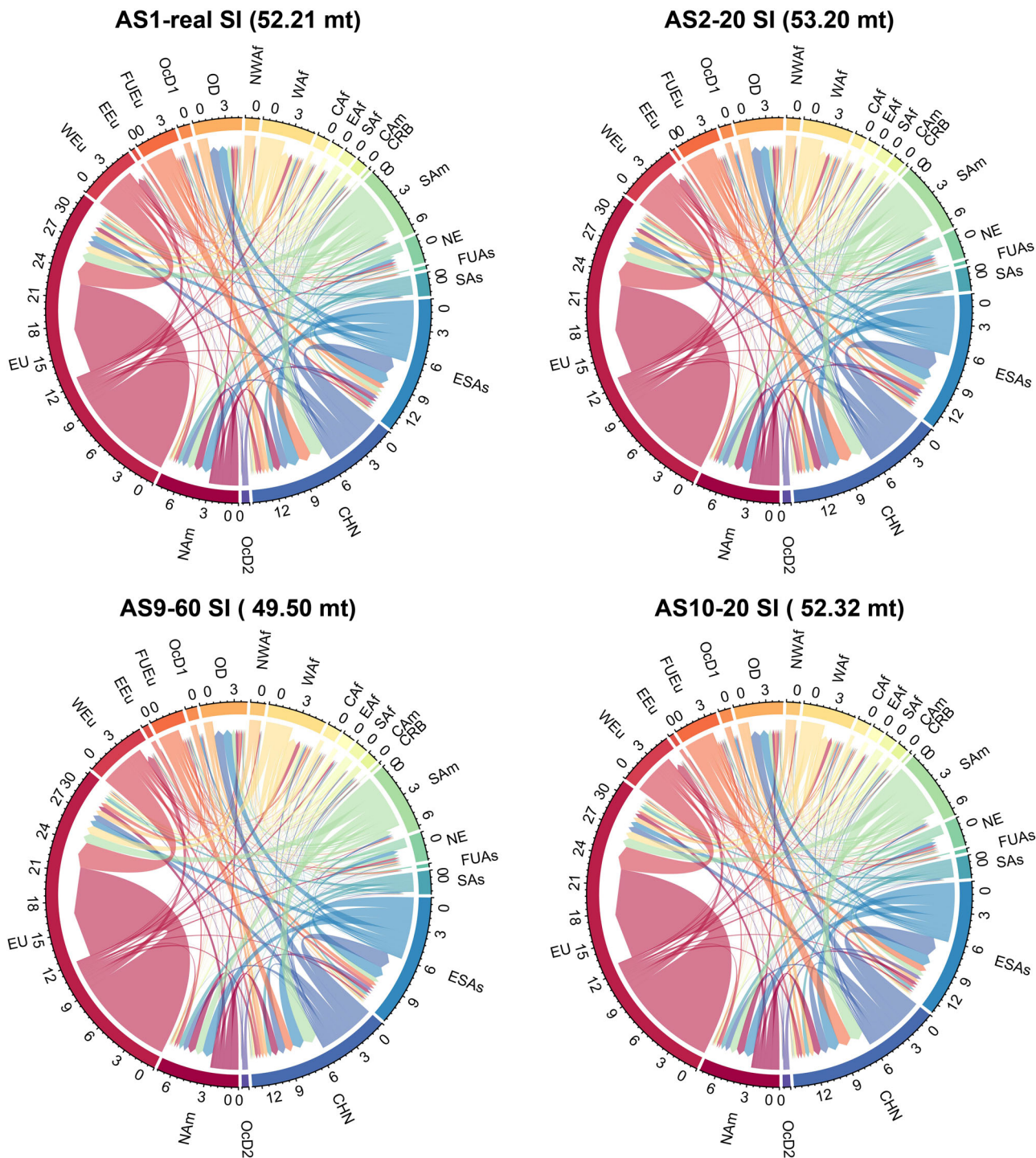


Fig. 7 Visualizing Trade network flow diagram for adjustment scenarios. Four scenarios AS1-real SI, AS2-20 SI, AS9-60, and AS10-20 SI are included.

developing countries. China and East-Southeast Asia, as the top two exporters in the global seafood market, play a crucial role in supporting crisis response and market resilience through multilateral cooperation.

In summary, the Geo-PN model offers a powerful tool for conducting a comprehensive assessment of the resilience of the global seafood network in response to pandemic shocks. By utilizing this model, we can delve deeper into the intricate dynamics within the seafood trade and evaluate the potential consequences of various scenarios. It provides valuable insights into recovery pathways and addresses the unique challenges faced

by developing countries. This enables us to develop effective strategies and policies aimed at revitalizing the seafood industry and ensuring long-term food security and nutritional needs for these nations. By leveraging the Geo-PN model, we can make informed decisions and take proactive measures to navigate the complexities of the seafood sector and build a more resilient and sustainable future.

Policy implications. To expedite the global seafood market recovery and reduce the seafood trade inequalities in developing countries, it is imperative for the Top5 exporters of developing

countries should work together and decrease their SI to ensure global seafood trade growth by 2030. Although the global seafood trade is hit less hard than the other food trade which dropped by 5.3%, the ongoing pandemic shock introduces unprecedented uncertainty to the global seafood network. This uncertainty has the potential to greatly affect poverty, hunger, and malnutrition.

The crisis of seafood supply in South Asia and Africa regions requires immediate and significant attention. Our analysis of 65 scenarios reveals alarming projections, indicating that by 2030, an average of 17 to 57 million people in developing regions will face insufficient seafood availability due to the lingering effects of the pandemic (refer to Table S5). Amongst these regions, South Asia stands out as a grave concern, as its population is expected to reach 1.7 billion by 2030 (FAO, 2020b). Unfortunately, the impact of the pandemic is anticipated to leave an estimated 347 million to 466 million people in this region unable to meet their seafood consumption needs. Eastern Africa and Western Africa are also poised to experience critical shortages, with an average of over 158 million and 156 million people, respectively, grappling with limited access to seafood. This highlights the urgent need for interventions and strategies to address the impending seafood supply crisis in these vulnerable regions.

Meanwhile, although network diversification can support developed countries to improve their resilience, network diversification has limited effectiveness in mitigating domestic demand and supply shocks. In the context of seafood trade, heavy reliance on transportation and ice infrastructure remains crucial. Despite available alternatives, rerouting can incur additional costs, and natural disasters can still increase transport costs. Moreover, countries such as small island states in Oceania, South America, etc., often lack alternative trade routes due to limited transport infrastructure and a higher dependency on a small number of shipping service providers. Consequently, these countries are more exposed to volatility in transport costs and are therefore more susceptible to shocks (Briguglio, 1995; Wilmsmeier and Hoffmann, 2008). Therefore, more concerns should be paid in these regions.

Finally, the adoption of knowledge-based, site-specific nutrient management in aquaculture in certain developing countries, as well as the implementation of free-trade agreements between developed and developing nations, will support fish farmers in developing regions to increase seafood production and enhance farmer profits. Concerns about the sustainable development of seafood production, aquaculture in particular, are not new in developing countries (Delgado, 2003; Xie et al., 2014). Low technology is used in non-fed and inland-fed aquaculture using extensive ponds, which is labor-intensive compared with mariculture in floating systems. OECD-FAO (2020) estimated that the annual average production of fish farmers in Norway was 195 tons per person, compared with 10 tons in Malaysia, about 7 tons in China, about 4 tons in Thailand, and only about 1 ton in India and Indonesia. The challenge is still how to increase yield while minimizing the negative environmental impact associated with intensive seafood production, as well as how to implement adaptation strategies to sustain aquaculture growth against a backdrop of rising temperatures and sea level rise (Kobayashi et al., 2015; Dey et al., 2016; Barange et al., 2018; Andronova et al., 2019).

Limitations and recommendations to further research. It is also admitted that there are some limitations of data sources and assessment methods in this cascading impact estimate. The paper assumes that the indicator of strictness of pandemic control policy provided by the OxCGRT project enables estimating the supply damage of seafood trade to some extent, but the specific

economic damage, such as the seafood-based livelihoods and seafood nutrition security, cannot be accurately estimated (Udmale et al., 2020; Naylor et al., 2021). Different region-specific constraints on global supply-chain scenarios can be adjusted by changing this stringency index. Meanwhile, compared with the International Model for OECD-FAO projects (Gephart and Pace, 2015; Herforth et al., 2020) (more details can be found in Fig. S6), our model does not consider factors such as economic fluctuations and climate change (Béné et al., 2015; Goh et al., 2021), but these factors can be expressed as interdependence and implemented in the model in the future. Besides, to fully understand the global seafood system, better data on the sector are critically needed. At present, there is no national-level data at a global scale to describe the geographic distribution or their total socio-economic contribution (Barange et al., 2018). National-level seafood trade data should be implemented in the future. Overall, the Geo-PN model offers the potential to evaluate the possible direct economic damage, as well as the amplified impacts of COVID-19 on the global seafood network (Otto et al., 2017; Inoue and Todo, 2019), while we need to further improve this model in the future to quantify the economic ripple effects of alternative seafood networks contributing to systemic resilience.

Data availability

The datasets generated during the current study are available from the corresponding author upon reasonable request.

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Author contributions

CZW: conceptualization, writing—review & editing, formal analysis, funding acquisition. MZ: methodology, software, formal analysis, data analysis, data collation, MZ has the same contribution as CZW; WC: data analysis, data collation; YG: methodology, supervision, manuscript revision. DPW: formal analysis, manuscript revision; DZ: software; DSX: conceptualization, supervision, manuscript revision; QMC, CXC, WGZ: manuscript revision.

Competing interests

The authors declare no competing interests.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Informed consent

This article does not contain any studies with human participants performed by any of the authors.

Additional information

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