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Spatio-temporal heterogeneity in the international trade resilience during COVID-19

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ABSTRACT

The COVID-19 pandemic and subsequent lockdowns have created immeasurable health and economic crises, leading to unprecedented disruptions to world trade. The COVID-19 pandemic shows diverse impacts on different economies that suffer and recover at different rates and degrees. This research aims to evaluate the spatio-temporal heterogeneity of international trade network vulnerabilities in the current crisis to understand the global production resilience and prepare for the future crisis. We applied a series of complex network analysis approaches to the monthly international trade networks at the world, regional, and country scales for the pre- and post- COVID-19 outbreak period. The spatio-temporal patterns indicate that countries and regions with an effective COVID-19 containment such as East Asia show the strongest resilience, especially Mainland China, followed by high-income countries with fast vaccine roll-out (e.g., U.S.), whereas low-income countries (e.g., Africa) show high vulnerability. Our results encourage a comprehensive strategy to enhance international trade resilience when facing future pandemic threats including effective non-pharmaceutical measures, timely development and rollout of vaccines, strong governance capacity, robust healthcare systems, and equality via international cooperation. The overall findings elicit the hidden global trading disruption, recovery, and growth due to the adverse impact of the COVID-19 pandemic.

1. Introduction

The COVID-19 pandemic has caused an unprecedented disruption to the global economy and world trade, bringing economic activity to a near-standstill as countries imposed social distancing and travel restrictions to halt the virus spread. The International Monetary Fund (IMF) estimates that the global economy shrank by 4.9% in 2020 (International Monetary Fund, 2020), which is the most serious global economic crisis since the Great Depression of the 1930s. COVID-19 has hit global supply chains badly because many factories were closed and production has halted. Exports and imports have been significantly affected due to the consumption slowdown in the world. Different countries have been experiencing different waves of COVID-19 and its variants, thereby resulting in the fragmentation of global trade and supply linkages.

Two years after the onset of the COVID-19 pandemic, the global economy stages its most robust post-recession recovery in 80 years with 5.6 percent growth in 2021 (The World Bank, 2021b). Though the total trade flows have surpassed pre-pandemic levels, the COVID-19 shows

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Abbreviation

ITN	International trade network
YoY	Year-on-Year
ADVEC	Advanced Economies
EU	European Union
DA	Emerging and Developing Asia
EDE	Emerging and Developing Europe
APQ	Asia and Pacific
WE	Latin America and the Caribbean
SSA	Sub-Saharan Africa
EAQ	East Asia
SEQ	Southeast Asia
MECA	Middle East and Central Asia
USA	United States
CHN	Mainland China
JPN	Japan
DEU	Germany
IND	India
GBR	United Kingdom
FRA	France
ITA	Italy
BRA	Brazil
CAN	Canada
RUS	Russian Federation
KOR	Korea, Rep. of
ESP	Spain
AUS	Australia
MEX	Mexico
IDN	Indonesia
NLD	Netherlands, The
SAU	Saudi Arabia
TUR	Turkey
CHE	Switzerland
TWN	Taiwan Province of People Republic of China

considerably diverse impacts across countries and regions. For example, the outlook for advanced economies has been expected to recover fast because of additional fiscal and monetary support as well as broader and faster vaccine roll-out (International Monetary Fund, 2021a). The economic prospects for the low-income developing countries are not promising because of the low vaccination percentage and tighter financing conditions (International Monetary Fund, 2021a; The World Bank, 2022). China experienced a sharp fall in exports during Feb 2020 with a quick recovery back to normal by Mar 2020, whereas the USA and European Union production had a later recovery in which there was a gap from historical trend volumes (OECD, 2022). Considering a high degree of uncertainty in the length and severity of the outbreak, as well as the trajectory of the recovery in the global economy, it is important to have a better understanding of the strengths and vulnerabilities of international trade networks (ITNs) in the context of the current crisis to evaluate global production resilience and be prepared for the future crisis.

Understanding the impact of the pandemic on international trade requires considering the interplay between public health measures (e.g., social distancing) and the need for economic recovery without human activity restrictions. Two competing rationales have emerged in the literature on this relationship. One argument in favor of lockdowns suggests that early, well-designed policies of lockdowns can yield net benefits for society, despite the high "price of life" (Balmford et al., 2020; Chowdhury et al., 2022; Dzúrová & Květoň, 2021). Some researchers further suggest that early and stringent implementation of non-pharmaceutical measures (i.e., lockdowns), and following farsighted policies (i.e., vaccination development), could result in a double dividend of improved public health and economic activity (Atkeson, 2021; Bajra et al., 2022). However, the opposing rationale suggests that the economic costs of lockdowns outweigh their benefits and that their effectiveness is uncertain (Allen, 2022; Coccia, 2021d, 2022b; Homburg, 2020; Wood, 2022). This view maintains that the society as a whole, rather than the lockdowns themselves, reduces fatality rates and negative effects on the economic system. For instance, Coccia (2021d) have noted that countries with previous high healthcare investments have been able to decrease COVID-19 fatality rates while implementing short but full lockdowns, preventing the contraction of economic growth.

Non-pharmaceutical measures, such as lockdowns and social distancing, inevitably place restrictions on international trade, which involves multiple types of social interactions, such as industrial and services activities, traffic, logistics, and group activities (Bontempi & Coccia, 2021; Bontempi et al., 2021; Romanillos et al., 2021). In addition, the fear of infections also drives people to disengage from commercial activities and has negative impacts on international trade (Goolsbee & Syverson, 2021). The economic crises accompanying COVID-19 also threaten the conditions of foreign trade agreements (Popkova & Andronova, 2022). This shock could lead to a disruption of world supply chains (Popkova & Andronova, 2022) and exacerbate the uncertainty of international trade via trade links (Crozet et al., 2022). During times of heightened uncertainty, the ability to reduce risks is crucial, including through global value chain participation (Wang et al., 2022), letters of credit (Crozet et al., 2022), and knowledge preparedness (Orlando et al., 2022).

Hence, there are diverse spatio-temporal factors that could impact international trade including dynamic pandemic waves over regions (Chowdhury et al., 2022), population density (Bayode et al., 2022; Chowdhury et al., 2022), seasonality (Coccia, 2022a), public health investment (Coccia, 2021b; 2022d), policy response and population cooperation (Coccia, 2021c; Dzúrová & Květoň, 2021), and supply chain resilience (Gnangnon, 2022). However, most studies have drawn their conclusions based on selective countries over short time periods such as countries (i.e., Italy, Spain, and France) with cultural and social similarities during the first wave of the pandemic (Atkeson, 2021; Coccia, 2021a; Homburg, 2020), and developed countries (Antonietti et al., 2022; Balmford et al., 2020; Coccia, 2022b; Vidya & Prabheesh, 2020). To obtain a comprehensive understanding of the spatio-temporal heterogeneity in international trade resilience during COVID-19, this study applies complex network analysis on the monthly international trade networks (ITNs) data for the pre- and post- COVID-19 outbreak periods to address the following questions.

- Q1: How does COVID-19 impact trade resilience in countries and regions with varying levels of containment efficiency over time?
- Q2: How does COVID-19 impact on trade resilience in countries and regions with different levels of economic development over time?
- Q3: How does COVID-19 impact on trade resilience in terms of globalization and regionalization over time?

2. Methods

2.1. Sample, data, and source

We collected international trade data from International Financial Statistics Database (International Monetary Fund, 2022) that includes monthly imports and exports for 177 countries or areas where the data are available from Jan 2018 to Dec 2021 in US dollars. We also collected

the 2019 annual Gross Domestic Product (GDP) for those countries in US dollars from the IMF (International Monetary Fund, 2022), while the missing values for Cuba and North Korea are obtained from the World Bank (The World Bank, 2021a) and Trading Economics website (Trading Economics, 2021). According to World Economic Outlook (International Monetary Fund, 2021b), ten geographical regions (see Appendix Table A. 1) with different levels of socio-economic development have been selected for our study (see Appendix Fig. A. 1).

2.2. Measures of variables

ITN consists of countries as nodes and trade linkages (i.e., imports and exports) as edges in a graph. This study defines two types of weighted directed ITNs (i.e., imports and exports). This study uses the original trading volume to define the weight of edges in the network in which we transform imports and exports into ITN trade matrices. To analyze trade resilience at the regional scale, we also build two types of regional ITNs: the intra-regional ITN comprises only countries and areas within the same region; the inter-regional ITN (e.g., East Asia – Emerging and Developing Asia) includes countries and areas within the two regions (e.g., countries and areas in East Asia or/and in Emerging and Developing Asia).

This study employs a series of measures to quantify interconnectedness, trade volume, centrality, and regionalization ratio as follows.

- Interconnectedness of ITN is quantified by its density, which is the proportion of actual edges to possible edges.
- Trade volume is measured by the weighted degree for countries and areas, and by the sum of weighted degree for regions and the globe. Weighted degree is calculated as the sum of weights of edges for nodes and therefore is used to represent the trade volume for countries and areas. Import trade volume is the sum of in-edge weights for each node, while export trade volume is the sum of out-edge weights.
- Centrality is quantified using PageRank centrality, which measures the importance of each node based on the number of incoming relationships and the importance of the corresponding source nodes according to their incoming relationships. Regions' average PageRank centrality is calculated as the mean value of PageRank centrality within each region. The formula to calculate PageRank is: $x_i = \alpha \sum_k^N \frac{a_{k,i}}{d_k} x_k + \beta$, where α and β are constants; d_k is the out-degree of node k if such degree is positive, or 1 if the out-degree of k is null; $a_{k,i}$ is the entry at row k and column i of the adjacent matrix $A = (a_{i,j})$. This study takes trade volume as edge weights.
- Regionalization ratio is the proportion of intra-regional trade volume to the total trade volume, reflecting the degree of regionalization in international trade. A larger ratio indicates a greater degree of regionalization, whereas a smaller ratio suggests a higher degree of globalization.

Resilience refers to the ability of a system to withstand and recover from the effects of hazards in a timely and efficient manner (Christopher & Peck, 2004; Melnyk et al., 2014). This capability can be evaluated from two aspects: robustness referring to a system's ability to maintain its function during hazards, and responsiveness referring to a system's ability to return to its original state or even improve upon it (Melnyk et al., 2014; Mena et al., 2022). While researchers have applied the YoY monthly percentage change in trade volume to capture degree of trade resilience over time (Mena et al., 2022), this study defines YoY monthly percentage change and the trade resilience based on the time series of the percentage change, in terms of robustness and responsiveness.

- The YoY monthly percentage change is calculated by comparing the percentage increase or decrease of a variable in a given month of 2020 or 2021 to the average value of the same variable in the corresponding months of 2018 and 2019. By using the average value of the variable in both 2018 and 2019 as the baseline, this study aims to minimize potential errors caused by emergencies or other interferences that could occur during a single year.
- This study defines robustness as the ability to maintain function during hazards and measures robustness as the worst status during hazards, given by: $Robustness_i = \begin{cases} 1, \min\,(YoY_{i,t}) \geq 0 \\ 1 + \min(YoY_{i,t}), \min\,(YoY_{i,t}) < 0 \end{cases}$ where i refers to the globe, a region, or a country; $YoY_{i,t}$ refers to its YoY monthly percentage change in trade volume at time t.
- This study defines responsiveness as the time from the worst status to recovery and measures responsiveness by calculating: $Responsiveness_i = \begin{cases} 1, \min\,(YoY_{i,t}) \geq 0 \\ 0, \min\,(YoY_{i,t}) < 0, YoY_{i,Dec\ 2021} < 0 \\ \frac{24 - (RM_i - WM_i)}{24}, \text{otherwise} \end{cases}$ where i refers to the globe, a region, or a country; $YoY_{i,t}$ refers to its YoY monthly percentage change in trade volume at time t. If it has not recovered to its pre-crisis status (i.e., $YoY_{i,Dec\ 2021} < 0$), its responsiveness is set as 0. If its trade volume has not contracted (i.e., $\min\,(YoY_{i,t}) \geq 0$), its responsiveness is set as 1. Otherwise, its responsiveness depends on RM_i and WM_i: RM_i is the month that trade entirely recover (i.e., $YoY_{i,t} \geq 0$ from then on), and WM_i is the month when $YoY_{i,t}$ reach its minimum value. Furthermore, in this case, responsiveness is normalized into the range from 0 to 1.

In addition to robustness and responsiveness, this study also employs YoY monthly percentage change to PageRank centrality and regionalization ratio to capture the dynamic changes in international trade.

2.3. Data analysis procedure

Firstly, this study constructs global, intra-regional, and inter-regional ITN using the original trading volume to define the weight of edges. *Secondly*, this study computes density of networks, and weighted degree and PageRank centrality of nodes for all three ITNs. *Thirdly*, this study calculates interconnectedness, trade volume, centrality, and regionalization ratio according to our definition. *Fourthly*, this study conducts YoY monthly percentage changes to the above four variables. Finally, this study uses time series of YoY monthly percentage changes to compute trade robustness and responsiveness.

All data analyses are performed with Python 3, and the Python package *NetworkX* is used to construct ITN and calculate network variables.

3. Results

Fig. 1 presents the YoY monthly percentage change in global interconnectedness and global trade volume. Global trade volume had been reducing since Jan 2020 and dropped sharply to its lowest point close to −30% in Apr 2020 and May 2020, due to the massive disruption in the global supply chain and international trade prohibitions and restrictions (Guan et al., 2020) caused by the pandemic outbreak. The total trade volume has recovered rapidly after the abrupt reduction and reached the pre-crisis level around Sep 2020. From Sep 2020 to Nov 2020, trade volume has fluctuated in a small range around the pre-crisis level. Since Dec 2020, trade volume has an increasing growth rate even reaching to 20% from Sep 2021. The analysis of the ITN during this period reveals an average robustness of 0.718 and an average responsiveness of 0.750.

The global interconnectedness change shows different patterns: 4% of trade linkages has been broken in Apr and May 2020; the number of trade linkages has bounced back to pre-crisis levels in Jun 2020 and started to increase in Sep 2020; the maximum growth rate of the number of trade linkages was about 4%. Those findings suggest that trade linkages have been quickly reestablished after being broken while the trade volumes were still in contraction.

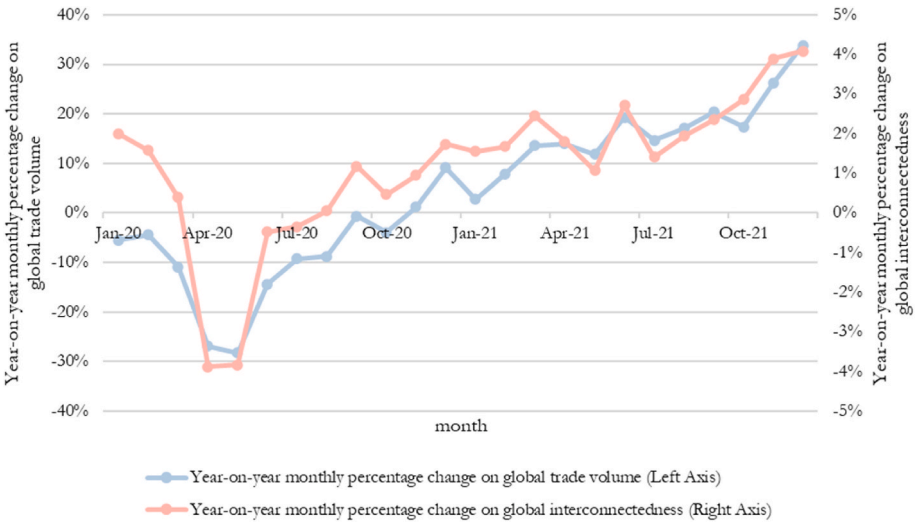

Fig. 1. The impact of COVID-19 on global trade networks.

Fig. B1 in the appendix illustrates the YoY monthly percentage changes in import and export trade volumes for each region in the global trade, sorted by their average GDP in 2019. All regions have been shrinking at the early stage of the pandemic, but different regions show dramatically diverse levels of trade robustness and responsiveness. Table 1 summarizes these measures for each region. East Asia (EAQ), Emerging and Developing Asia (DA), and Asia and Pacific (APQ) have demonstrated the strongest trade robustness, with values above 0.8, followed by Southeast Asia (SEQ, 0.701), Advanced Economies (ADVEC, 0.699), Emerging and Developing Europe (EDE, 0.667), European Union (EU, 0.665), and Latin America and the Caribbean (WE, 0.635). Sub-Saharan Africa (SSA) and Middle East and Central Asia (MECA) have exhibited the weakest trade robustness, with a value of 0.552 and 0.476, respectively. Additionally, APQ have demonstrated the highest export responsiveness, with a value of 0.833, followed by DA and EAQ, while other regions have demonstrated lower export responsiveness than the global average of 0.750.

Although import robustness and responsiveness tend to exhibit less variation across regions than export volume, some regions still showed significant differences in their performance. Although the import robustness of APQ, DA, EAQ were lower than their export robustness, these regions still have demonstrated the best import robustness, with EAQ having the highest value of 0.845. Other regions excluding WE have shown better import robustness than their export robustness. WE appeared to be the most vulnerable region in terms of import robustness. Most regions have witnessed an import responsiveness ranging from 0.7 to 0.8. However, ADVEC and EU have shown the worst import responsiveness, mainly due to the belated import decline in Jan 2021, as shown in Appendix Fig. B1(b) . Surprisingly, EDE have presented the best import responsiveness, with a value of 0.833.

Table 1
Trade resilience of regions, in terms of robustness and responsiveness.

Region	Robustness		Responsiveness	
	Export	Import	Export	Import
EAQ	0.870	0.845	0.750	0.750
ADVEC	0.699	0.729	0.625	0.625
DA	0.883	0.747	0.750	0.750
EU	0.665	0.666	0.583	0.583
APQ	0.821	0.754	0.833	0.708
SEQ	0.701	0.716	0.750	0.708
EDE	0.667	0.715	0.583	0.833
WE	0.635	0.569	0.625	0.708
MECA	0.476	0.670	0.500	0.708
SSA	0.552	0.653	0.542	0.708
EAQ[a]	0.765	0.794	0.750	0.708
DA[a]	0.735	0.608	0.708	0.708
APQ[a]	0.729	0.700	0.750	0.708

Notes.
[a] Means excluding Mainland China. Regions are sorted by the average GDP in 2019.

Given that Mainland China has been included in EAQ, DA, and APQ, we additionally provide the trade robustness and responsiveness of these three regions in Table 1. A comparison of these measures reveals that the advantage of trade resilience has disappeared for DA and APQ when Mainland China is excluded. The advantage of EAQ has weakened, but it still outperformed the other regions. This comparison indicates that Mainland China has played a leading role in determining regional trade resilience during COVID-19.

To gain a deeper understanding of trade resilience across regions, we conducted an analysis of intra-regional and inter-regional trade resilience, as presented in Figs. 2 and 3. Our findings are consistent with the observations made in Table 1. Specifically, EAQ, DA, and APQ continued to exhibit the highest robustness for both intra-regional and regional trade, followed by ADVEC, EDE, and EU. SEQ, EDE, WE, MECA, and SSA have displayed the weakest robustness. Notably, all inter-region trades involving EAQ, DA, and APQ have exhibited high robustness. This may explain why the intra-regional trade robustness of SEQ is low, but its regional robustness is relatively high: EAQ has become a crucial partner of SEQ. Inter-regional trade involving ADVEC and EU have demonstrated moderate robustness, whereas inter-regional trade between the rest low-income regions (e.g., SEQ, EDE) have displayed the most vulnerable robustness.

The distribution of intra- and inter-regional responsiveness follows a similar pattern as that of the intra- and inter-regional robustness. DA, APQ, and EAQ are the regions with the best intra-regional responsiveness, followed by MECA, SEQ, ADVEC, and EU. Furthermore, all inter-region trades involving EAQ, DA, and APQ have exhibited high responsiveness, while inter-regional trade involving ADVEC EU, and EDE have demonstrated moderate responsiveness.

Given the differences in trade resilience levels across regions, it is natural to question whether these differences have influenced the structure of trade networks in terms of centrality and trend of regionalization or globalization. The results are shown in Figs. 4 and 5. Fig. 4 (a) and (c) present the regional YoY monthly percentage changes in the average PageRank for all countries. Considering Mainland China's significant impact on corresponding regions, we also present the same changes of EAQ, DA and APQ excluding Mainland China in Fig. 4(b) and (d). Fig. 4 indicates which regions lead a shift towards the international

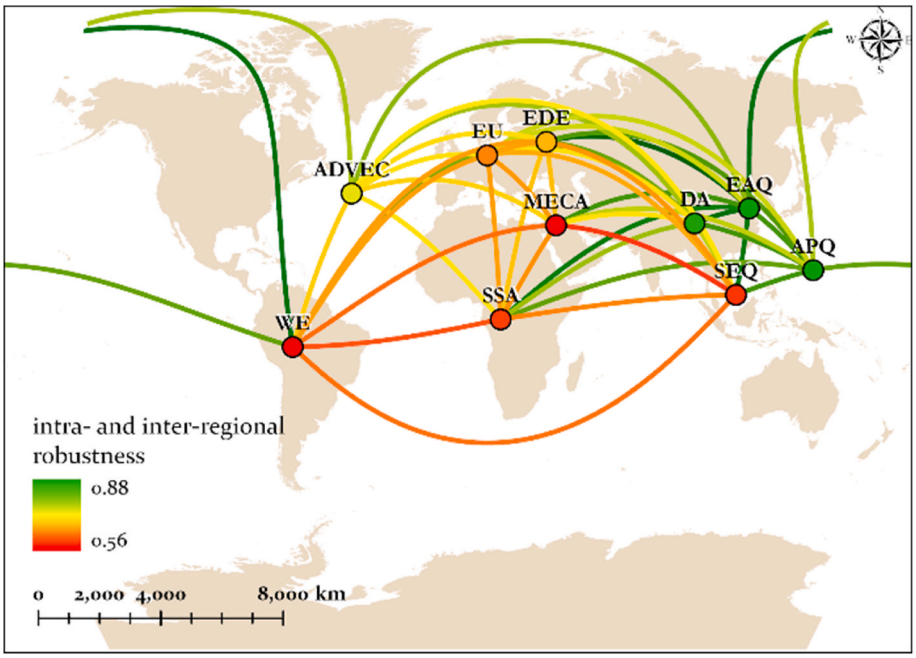

Fig. 2. Intra- and inter-regional robustness. The color scheme from red to green indicates low robustness to high robustness of intra-regional trade volume (for nodes) and inter-regional trade volume (for lines). Regions are symbolized as node due to the overlapping among some regions.

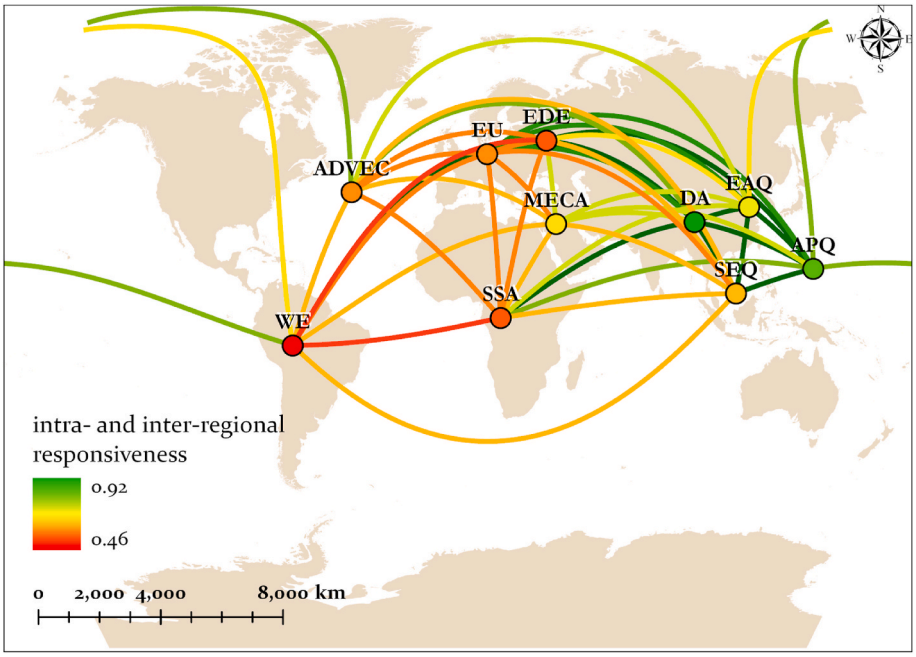

Fig. 3. Intra- and inter-regional responsiveness. The color scheme from red to green indicates low responsiveness to high responsiveness of intra-regional trade volume (for nodes) and inter-regional trade volume (for lines). Regions are symbolized as node due to the overlapping among some regions.

trade center (positive values) or towards the trade edges (negative values) compared to the pre-Covid. We could observe some obvious patterns in terms of export PageRank centrality: 1) EAQ, DA, APQ, and SEQ keep in a continuous rise around 10%; 2) ADVEC and EU have a reduction around 5%; 3) EDE, WE, SSA and MECA have evolved back to pre-crisis levels. It indicates that the global export PageRank centrality has shifted slightly from ADVEC and EU to EAQ, DA, APQ, and SEQ. Imports show a similar trend but less obvious extent as the exports. Fig. 4 (b) shows that Mainland China plays a driver role in the regional export centrality shift.

Fig. 5 presents YoY monthly percentage change in regionalization ratio for both imports and exports from 2020 to 2021. In terms of exports, most regions including EAQ, ADVEC, DA, EU, APQ, and EDE do not exhibit obvious trends. SEQ went through a consistent decline of export regionalization ratio. It might be explained by an effective COVID-19 containment in SEQ that serves one of the major exporting places with increasing demand around the world (World Trade Organization, 2020, 2021a, 2021b). Both MECA and SSA experienced increasing export regionalization ratios during COVID-19, which reinforces that low-income countries move towards the trade network

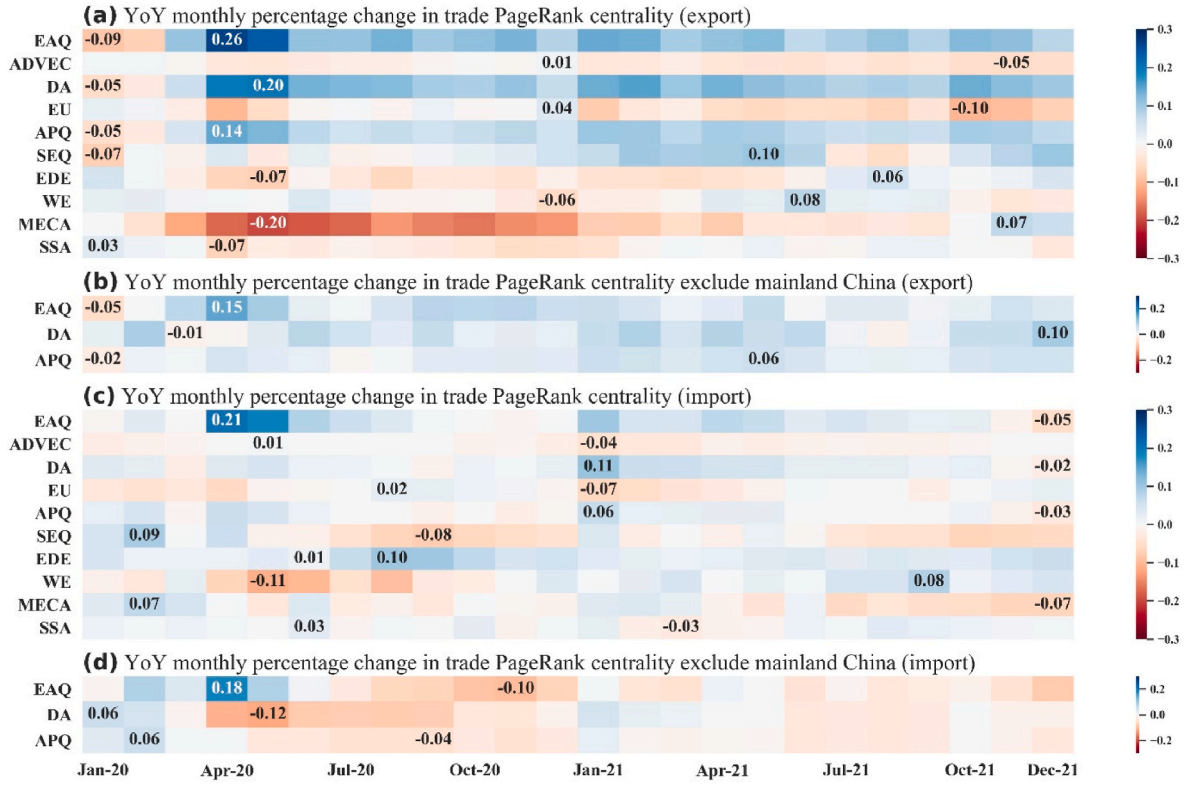

Fig. 4. YoY monthly percentage change in trade PageRank centrality including both imports and exports across regions. X-axis refers to months, and y-axis are the regions sorted by the average GDP in 2019. The color scheme from red to blue indicates decline to growth of trade PageRank centrality at the regional scale.

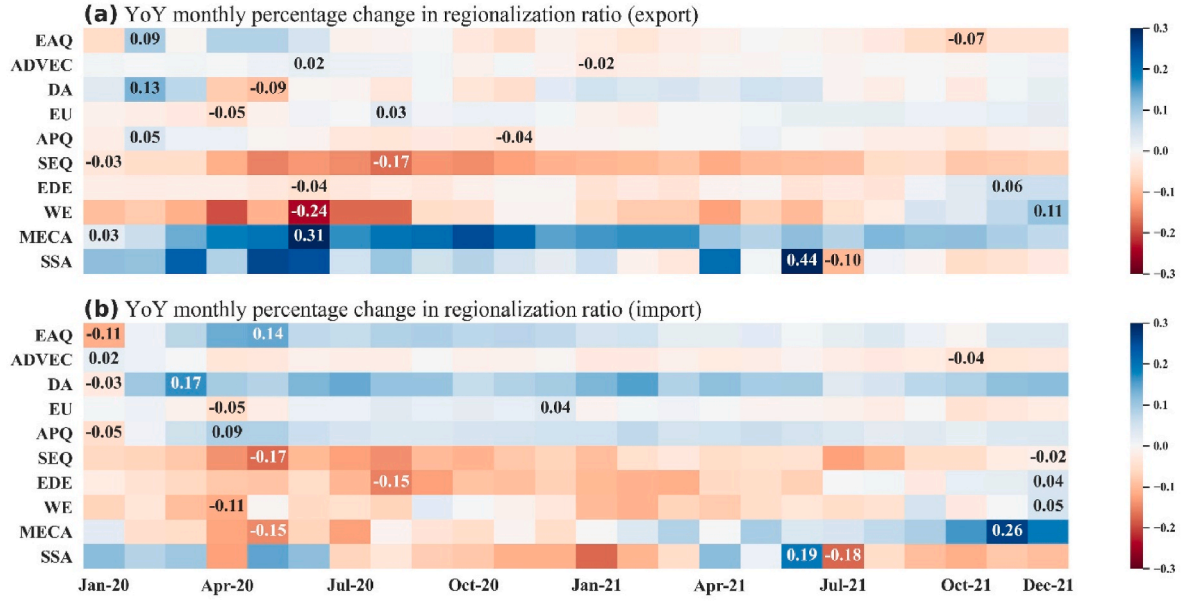

Fig. 5. YoY monthly percentage change including both imports and exports in regionalization ratio. X-axis refers to months and y-axis is the regions sorted by the average GDP in 2019. The color scheme from red to blue indicates decline to growth of regionalization ratio.

edges with their regional trading countries.

In terms of imports, DA, APQ, and EAQ exhibited slight regionalization trends, which indicates that those countries tend to increase their imports within regions due to more effective COVID-19 containment compared to the rest of the world (Chorzempa & Huang, 2021; Ma et al., 2021; Sachs, 2021). ADVEC and EU, as the high-income regions, show similar regionalization and globalization trends compared to pre-COVID. SEQ, EDE, and WE experienced import globalization trends in the most month during COVID-19, whereas MECA and SSA exhibited a mixed import regionalization and globalization over 2020 and 2021.

We conduct country-scale analyses from two aspects, including all countries and the top 20 countries with the highest GDP. Fig. 6 presents the export and import robustness and responsiveness of individual countries and areas. A comparison of Figs. 2 and 6 reveals the heterogeneity within regions. The high robustness of DA is primarily due to Mainland China and SEQ countries, while India does not contribute to it.

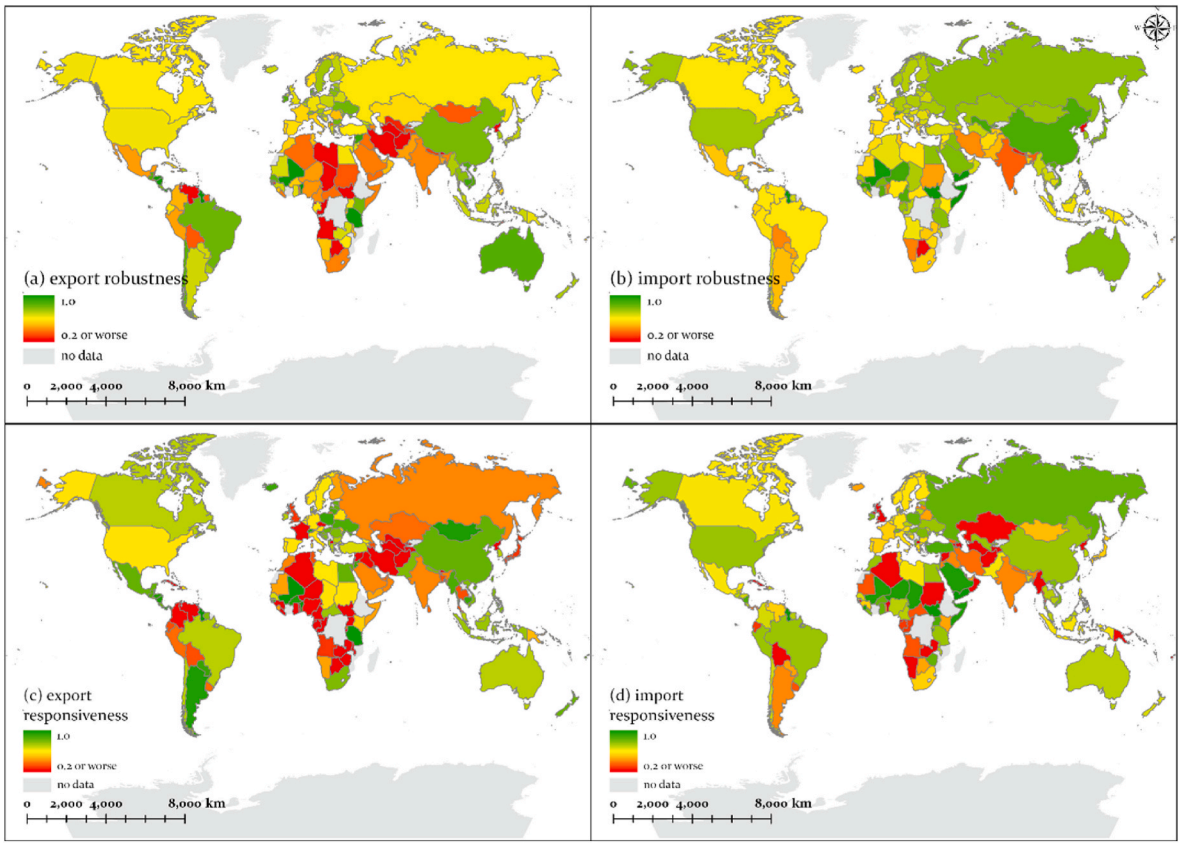

Fig. 6. Export and import robustness and responsiveness of countries and areas. The color scheme from red to green indicates low robustness (or responsiveness) to high robustness (or responsiveness) of countries and areas.

Similarly, in addition to East Asia countries and areas, Australia plays an important role in the high robustness of APQ. The moderate robustness of EU is attributable to the relatively low robustness of several countries such as France, Italy, and Spain. The United States and Canada have not demonstrated high level of robustness, and hence the robustness of ADVEC has not performed better than that of EU, while Australia, Japan, and South Korea have shown a relatively high robustness. Countries within MECA and SSA have generally exhibited low export robustness, while countries within WE have generally displayed low import robustness.

Regarding responsiveness, the spatial distribution of responsiveness across countries and areas is similar to that of robustness. However, Russia, France, and the United Kingdom have displayed notably low export responsiveness. Furthermore, Western European countries have generally illustrated an inferior import responsiveness, resulting in an import responsiveness value of 0.583 for EU.

Fig. 7 presents the YoY monthly percentage changes in both trade volume and PageRank centrality for all 177 countries sorted by GDP in 2019. Countries with higher GDP show a clear trend of disruption-recovery-growth on trade export volume compared to countries with lower GDP that shift around sharp fall and rise. It indicates that high-income countries maintain stronger trade robustness and responsiveness whereas low-income countries exhibit a sign of vulnerability when facing COVID-19. Compared to the export volume patterns, more countries with high GDP show clear disruption-recovery-growth patterns. Relating to the comparison between export and import volume at the regional scale, both indicate that the global import across regions and countries present more resilience compared to the export during COVID-19.

The trade PageRank centrality changes at the country level do not show a clear pattern in terms of high and low GDP countries, but they show diverse patterns across different countries. It provides the evidence that more resilient countries during COVID-19 shift towards the international trade center whereas less resilient countries become peripheral and shift away from the international trade center. The export centrality for countries with the lowest GDP has hardly changed, suggesting that the pandemic has brought no opportunities but only disruptions to these countries.

Figs. 8 and 9 focus on the top 20 countries with the highest GDP in 2019 and their highest importing and exporting countries over different time periods during COVID-19. According to the above global-scale analyses, we selected four different time periods: 1) pre-Covid from 2018 to 2019; 2) disruption from Apr. 2020 to May 2020; 3) near recovery over Sep 2020; 4) growth from Nov 2021 to Dec 2021.

During the pre-Covid time period, United States, Mainland China, and Germany are the largest export trade countries for the top 20 countries. During the disruption time period, we can observe some obvious shifts in terms of the largest export trade countries: Germany to the United States for Switzerland; the United States to Mainland China for Japan; and the United States to Mainland China for Germany. The first two shifts remain the same while the third one has shifted back after the disruption time period. The majority of the highest export volume has declined from Apr 2020 to May 2020, except the export volume of Australia and Brazil to Mainland China as well as Switzerland to the United States. During the recovery time period, most links have recovered except the link from Saudi Arabia to Mainland China and from the United Kingdom to the United State. During Nov and Dec 2021, all the links become wider except one from the United Kingdom to the United States.

There are twenty-one nodes including Taiwan province of China in Fig. 6 because it is the largest import area to Mainland China during the four time periods. Mainland China is the largest importing country for eight out of the top 20 countries during pre-COVID, eleven out of the top 20 countries from Apr to May 2020, nine out of the top 20 in Sep, and

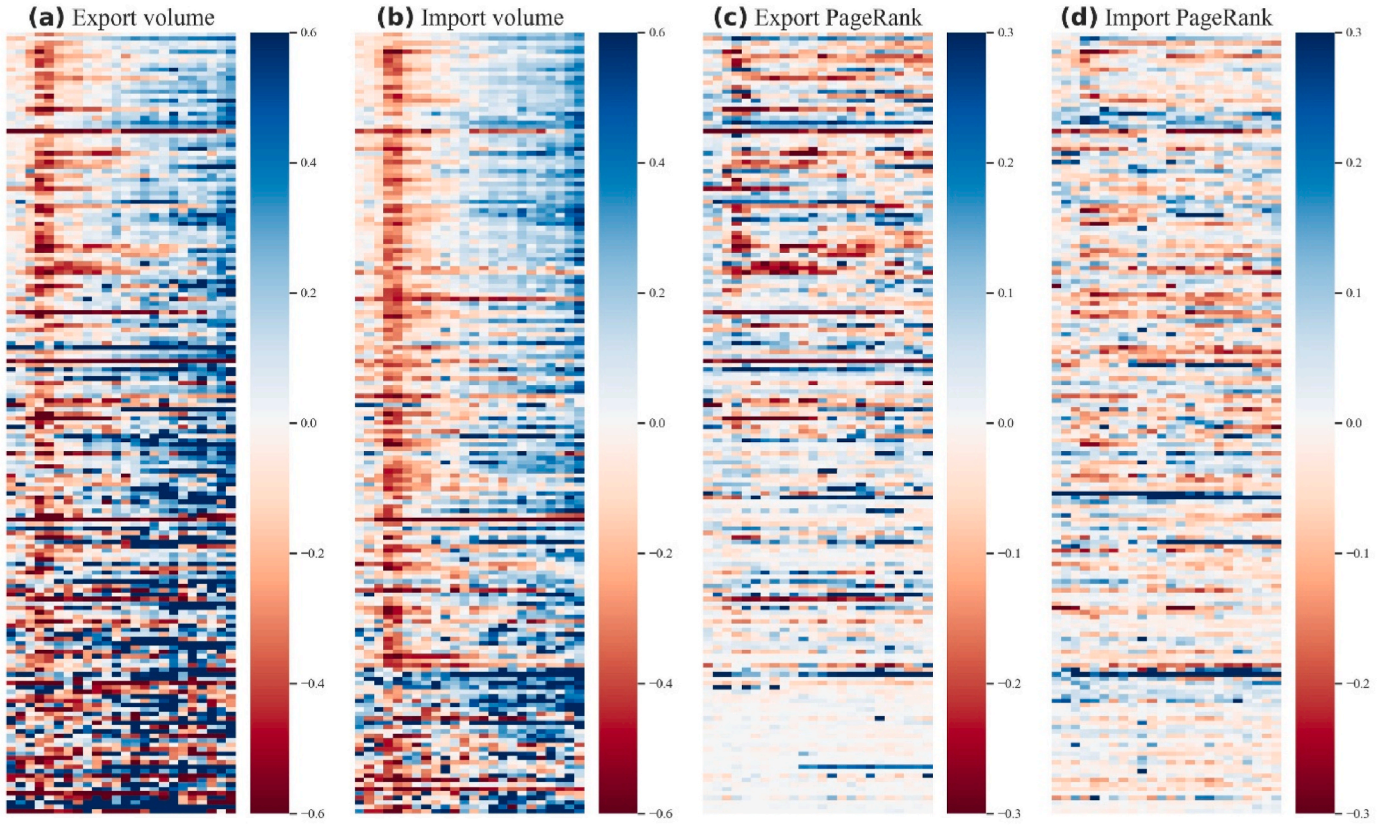

Fig. 7. YoY monthly percentage change in both trade volume and PageRank centrality including both imports and exports. X-axis for each heatmap refers to months, ranging from Jan 2020 to Dec 2021. Y-axis are all the countries sorted by GDP from the highest to the lowest in 2019. The color scheme from red to blue indicates decline to growth of trade volume (the left two) and trade PageRank centrality (the right two) at the country-scale.

twelve out of the top 20 from Nov to Dec 2021. It implies that Mainland China moved towards the center of import trade networks among the top 20 countries.

Overall, our analysis has revealed that regional trade resilience varies significantly, with DA, EAQ, and APQ exhibiting the best trade resilience at regional, intra-regional, and inter-regional scales. SEQ also has displayed relatively high trade resilience at regional and inter-regional scales due to its strong trade ties with EAQ, although it has been weaker at the intra-regional scale. Meanwhile, the two developed regions, ADVEC and EU, have exhibited only moderate trade resilience. WE, MECA, and SSA, where most of the least developed countries (LDCs) are located, have demonstrated correspondingly high trade vulnerability. These regional-scale patterns suggest that the level of economic development is not the sole determinant of trade resilience. Effective COVID-19 containment measures and strong trade linkages with resilient regions may also contribute to higher trade resilience.

At the country-scale, the heterogeneity of trade resilience is more evident: countries within the same region exhibiting significant differences in trade resilience. Notably, Mainland China has demonstrated strong trade resilience across all aspects, including its impact on the trade resilience of DA, EAQ, and APQ, as well as its influence on the top 20 countries in GDP. This achievement can be attributed, in part, to the "dynamic zero-COVID" policy implemented by the Chinese government. Similarly, Australia and New Zealand have exhibited high trade resilience due to their lack of land borders with other countries, which reduces the number of import cases caused by neighboring national boundaries. Southeast Asian countries have also shown trade resilience at both regional and inter-regional scale, which may be explained by effective COVID-19 containment, their close ties with China, and their roles as one of the major exporting places with increasing demand around the world (World Trade Organization, 2020, 2021a, 2021b).

4. Discussions

This study shows a comprehensive analysis of the effects of COVID-19 in the international trade during pre- and post- COVID-19. The findings indicate that countries that implemented effective COVID-19 containment measures, such as those in the Asia-Pacific region, tend to experience a positive impact on the international trade, resulting in a shift into center of international trade network. These measures included shorter periods of national lockdowns to contain the spread of COVID-19. For example, Sachs (2021) shows that Asia-Pacific countries have successfully suppressed COVID-19 through effective containments, resulting in low levels of community transmission. Moreover, our study reveals that countries with high levels of vaccination, such as those in the North Atlantic region (Mathieu et al., 2021), tend to resist the long-term disruptions on international trade during the first wave of the pandemic. This finding is consistent with established research on factors contributing to the rapid development and rollout of vaccines, such as good governance (Benati & Coccia, 2022), and high levels of democratization (Coccia, 2022c). This study also highlights that those countries without both effective COVID-19 containment and optimal levels of vaccination, such as many African and Latin American countries (Beaumont, 2021; Kirk & Duncan, 2021), tend to be more vulnerable in terms of international trade.

Our analysis also reveals significant spatio-temporal heterogeneity in trade resilience among countries and regions. The heterogeneity may be interpreted through studies focusing on the factors influencing the countries' trade resilience, especially during uncertainty times (Crozet et al., 2022; Gnangnon, 2022; Nitsch, 2022; Orlando et al., 2022; Wang et al., 2022). Particularly, Mena et al. (2022) argue that socio-economic and health inequalities, reflected in social and economic globalization, logistics performance, healthcare preparedness, and income level,

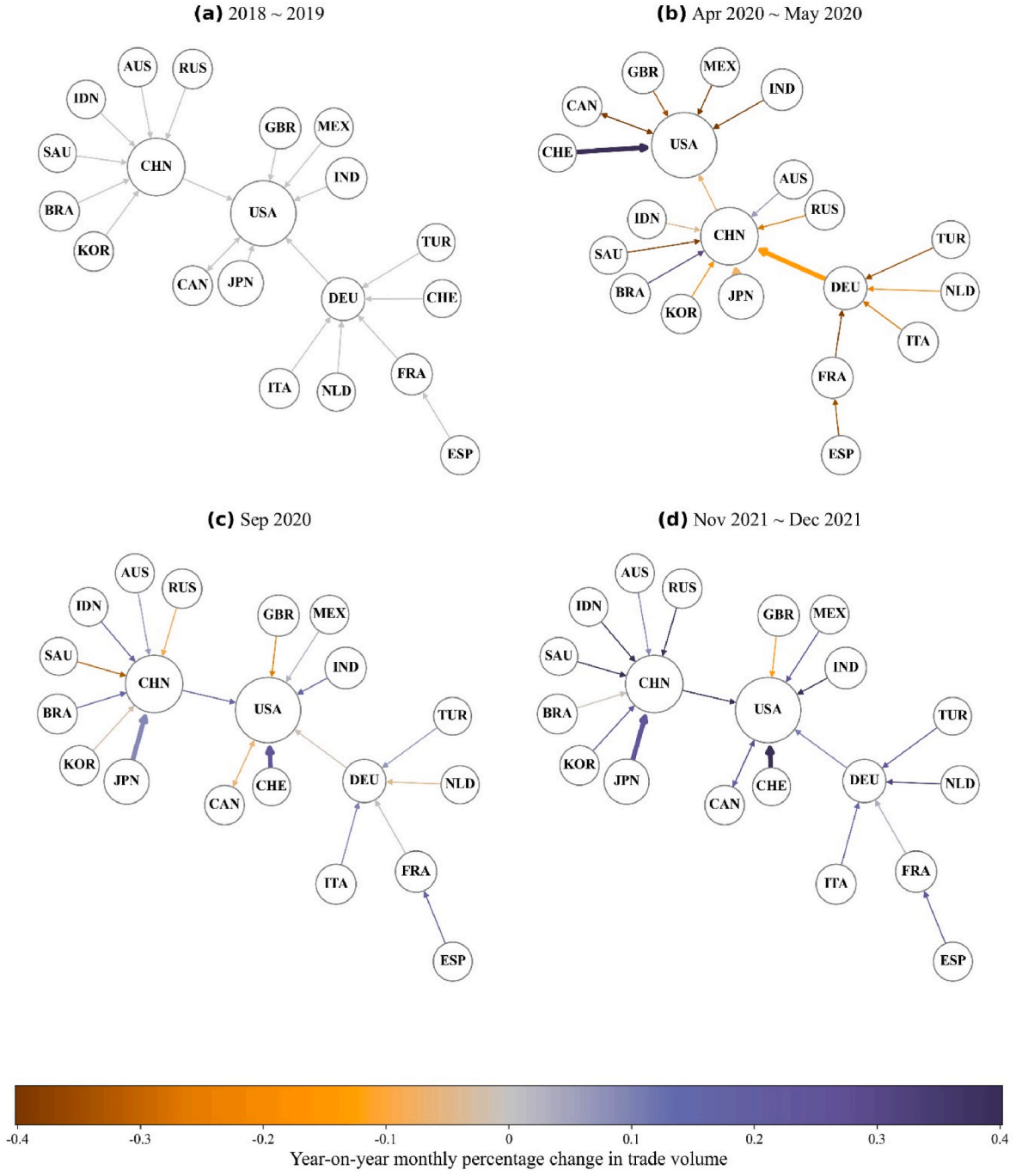

Fig. 8. Top 20 countries in GDP and their highest exporting countries. Each node represents one country: USA - United States; CHN - Mainland China; JPN - Japan; DEU - Germany; IND - India; GBR - United Kingdom; FRA - France; ITA - Italy; BRA - Brazil; CAN - Canada; RUS - Russian Federation; KOR - Korea, Rep. of; ESP - Spain; AUS - Australia; MEX - Mexico; IDN - Indonesia; NLD - Netherlands; SAU - Saudi Arabia; TUR - Turkey; CHE – Switzerland. Directed link from country A to country B indicates that B is the largest export trade country of A. The color of link indicates the average of YoY monthly percentage change in trade volume compared to the corresponding month from 2018 to 2019. The color scheme from red to blue indicates decline to growth of trade volume between countries. The link with width indicates an emerging highest exporting pair between two countries compared to pre-COVID. The node size indicates the GDP in 2019 with a larger node size representing a higher GDP value.

contribute to trade resilience of countries. However, Antonietti et al. (2022) argue that the number of infections and fatalities is positively correlated with centrality in the international trade network. This indicates that the outcomes of inequality are not only for vulnerable countries, but for the whole world via trade networks. Considering the highly interconnected world, this study argues that international cooperation and aid can not only suppress COVID-19 but also help economic recovery. Our study also reveals that the Asia-Pacific region, where COVID-19 has been effectively controlled, has experienced sustained import regionalization, indicating the potential benefits of international cooperation for economic recovery.

Drawing on our research and established literature, we propose several recommendations for addressing potential future pandemics. Our central argument is that effective containment measures can enhance trade resilience, so we propose several strategies for improving the effectiveness of such measures. Firstly, policymakers should

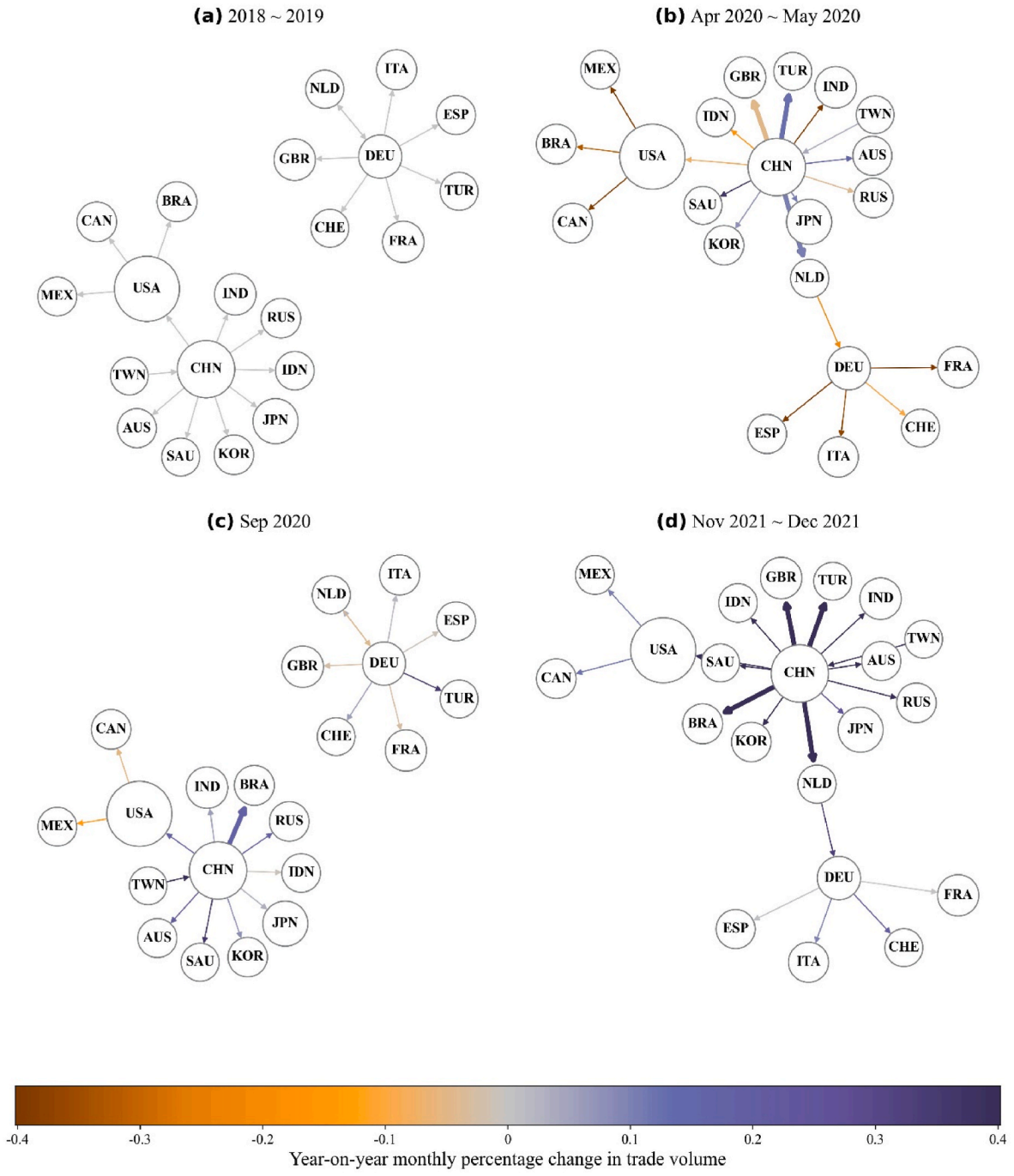

Fig. 9. Top 20 countries in GDP and their highest importing countries or areas. Each node represents one country: USA - United States; CHN - Mainland China; JPN - Japan; DEU - Germany; IND - India; GBR - United Kingdom; FRA - France; ITA - Italy; BRA - Brazil; CAN - Canada; RUS - Russian Federation; KOR - Korea, Rep. of; ESP - Spain; AUS - Australia; MEX - Mexico; IDN - Indonesia; NLD - Netherlands, The; SAU - Saudi Arabia; TUR - Turkey; CHE - Switzerland; TWN - Taiwan Province of People Republic of China. Directed link from country A to country B indicates that B is the largest trade importing country of A. The color of link indicates the average of YoY monthly percentage change in trade volume compared to the corresponding month from 2018 to 2019. The link with width indicates an emerging highest importing pair between two countries compared to pre-COVID. The color scheme from red to blue indicates decline to growth of trade volume between countries or areas. The node size indicates the GDP in 2019 with a larger node size representing a higher GDP value.

implement proactive measures before a pandemic outbreak to control its spread at an early stage (Lai et al., 2020; Jusup et al., 2022). Research suggests that the quality, rather than the length, of non-pharmaceutical interventions is crucial for their effectiveness (Coccia, 2021a; 2021d). Long-term non-pharmaceutical measures can quickly lose their impact and result in social and economic crises (Antonietti et al., 2022; Coccia, 2021a). Thus, timely intervention is critical to prevent a vicious cycle (Yin et al., 2021). Secondly, with early interventions showing their effectiveness, countries should work together to develop vaccines to reduce mortality and prevent healthcare collapse when the effects of non-pharmaceutical interventions diminish (Atkeson, 2021). Thirdly, improving governance capacity and healthcare system structures can complement the above two suggestions. Research shows that countries with strong governance and healthcare structures are better equipped to implement effective non-pharmaceutical interventions (Coccia, 2021d) and vaccination (Benati & Coccia, 2022). Fourthly, developed countries

should aid underdeveloped countries to prevent them from being adversely affected by pandemics, including development aid (Gnangnon, 2022), as well as the provision of medical supplies and vaccines.

5. Conclusions

COVID-19 spread across the world at a rapid pace, causing a tremendous impact on human health and economic loss. Though the outbreak began in China, to which the rest of EAQ, SEQ, and APQ are very closely connected by travel and trade, the success of those regions in suppressing the pandemic has been consistent since Spring 2020 (Sachs, 2021). Such a success guaranteed their strong trade resilience during COVID-19. In comparison, USA and EU have recorded very high infection rates (Chorzempa & Huang, 2021), which could greatly impact international trade at the beginning of COVID-19 outbreak. Those advanced economies have recovered at a moderate rate with monetary support and wide vaccine roll-out. Low-income regions with low vaccination rates and tighter financing conditions exhibited the weak vulnerability. An important lesson for the world to learn from the pandemic is to take collective responsibility to protect health and economic prosperity in the face of the global challenges such as COVID-19 and climate change.

We conclude by acknowledging the limitations of our study and suggesting directions for future research. Firstly, our analysis only focuses on aggregate bilateral trade and not on trade impacts on specific goods and products. Secondly, our study did not address the impacts of the pandemic on trade in services, such as tourism, which has been significantly affected due to travel restrictions.

To conclude, this study encourages a series of effective strategies to reduce the negative impact of future pandemic threats to economic activities. They include effective non-pharmaceutical measures, timely development and rollout of vaccines, strong governance capacity, robust healthcare system structures, and health equality via international cooperation and aid. In particular, a comprehensive strategy to prevent future pandemic from damaging health and society should be designed to assist policymakers in assessing manifold factors not only including sustainability, public health, and economy.

Data availability statement

Data can be downloaded at https://github.com/GeoSpatialX/TradeResilience_COVID.

Code availability

Code can be downloaded at https://github.com/GeoSpatialX/TradeResilience_COVID.

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Author contributions

Wei Luo: Conceptualization, Methodology, Supervision, Writing-original draft, Writing-review and editing, Funding acquisition, Project administration; Lingfeng He: Methodology, Software, Validation, Formal analysis, Data curation, Writing-original draft, Writing-review and editing; Zihui Yang: Methodology, Data curation, Formal analysis; Shirui Zhang: Data curation, Investigation, Writing-original draft; Yong Wang: Conceptualization, Supervision, Writing-review and editing; Dianbo Liu: Methodology, Writing-review and editing; Sheng Hu: Methodology, Writing-review and editing; Li He: Supervision, Writing-review and editing; Jizhe Xia: Supervision, Writing-review and editing; Min Chen: Writing-review and editing.

Declaration of competing interest

The author(s) declare no competing interests.

Appendix A. Details about Regions

Table A. 1
Names and Abbreviations of Analytic Regions

Abbreviation	Name
ADVEC	Advanced Economies
EU	European Union
DA	Emerging and Developing Asia
EDE	Emerging and Developing Europe
APQ	Asia and Pacific
WE	Latin America and the Caribbean
SSA	Sub-Saharan Africa
EAQ	East Asia
SEQ	Southeast Asia
MECA	Middle East and Central Asia

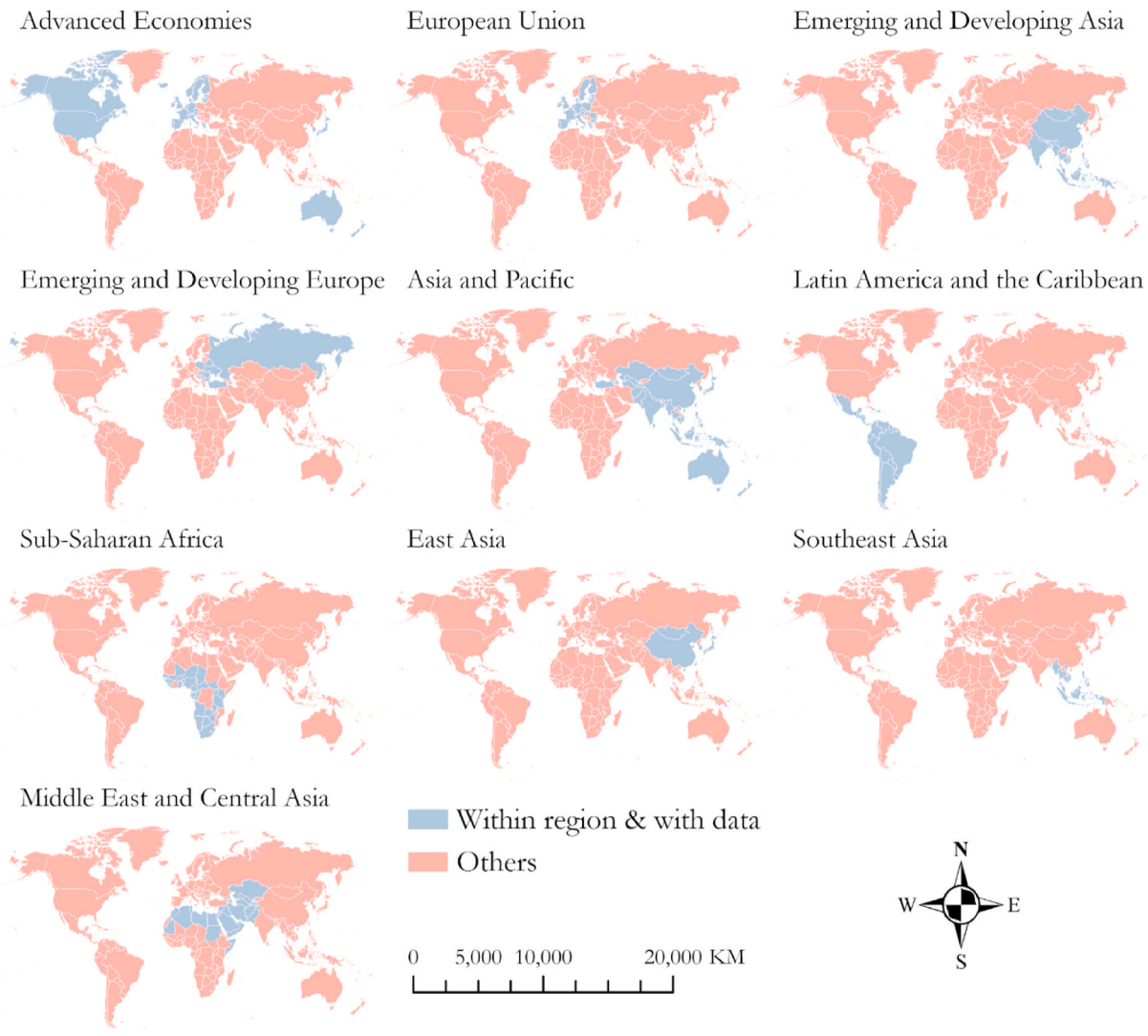

Fig. A. 1. Countries or areas within each analytical region. Blue color indicates the corresponding countries within the analytical region. Red color indicates the countries outside of the analytical regions or without international trade data.

Appendix B. Dynamics of trade volume across regions and countries

Fig. B1 (a) and Fig. B1 (c) present the YoY monthly percentage changes in both import and export trade volumes in the global trade for each region which is sorted by the average GDP in 2019.

The majority of regions have shown increments after the full recovery to pre-crisis levels at the end of 2020. EAQ, DA, and APQ have been with a consistently high growth rate of more than 20% since Feb 2021. Economic advanced regions, including ADVEC and EU, have kept a consistent moderate increment rate in export trade around 10% since Mar 2021. The export growth of SEQ, WE, SSA, and EDE fell into the middle of the above two regions and the former three experienced a lower increment rate during the peak of Delta outbreak around Jul and Aug 2021 (Luo et al., 2022). MECA experienced the longest export decline until Apr 2021, the lowest increment ranging from 1% May 2021 to 13% Oct 2021, and therefore the most vulnerable responsiveness equal to 0.5. All regions reach their peak of export growth in Dec 2021. Those regional patterns imply that an effective COVID-19 containment may play a major role in determining the export trade resilience, followed by economic development levels.

All regions have fully recovered at the end of 2020 and import increments over 2021 for all regions show a high correlation with export increments.

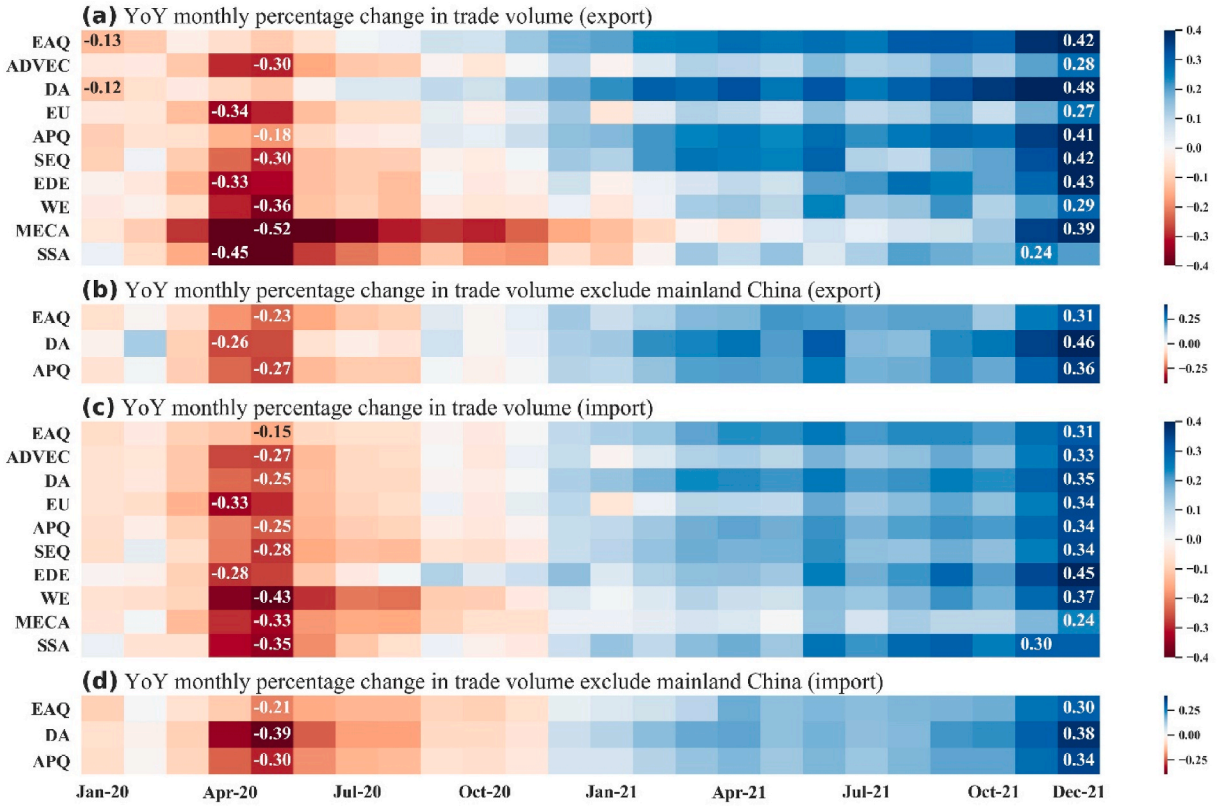

Fig. B.1. YoY monthly percentage change in trade volume including both imports and exports across regions. X-axis refers to months (e.g., Jan-20 means Jan. 2020), and y-axis are the regions sorted by the average GDP in 2019. The color scheme from red to blue indicates decline to growth of regional-scale trade volume. Only the maximum and minimum values are an noted in the figure.

Fig. B2 (a) present the YoY monthly percentage changes in intra-regional trade volumes for each region which is sorted by the average GDP in 2019. Comparing Fig. B1 to Fig. B2 (a), we can observe consistent patterns between intra-regional trade volume and global trade volume, implying the similar COVID-19 impacts. Specifically, EAQ, DA and APQ experienced a slight and momentary decline, followed by a strong recovery and growth. ADVEC and EU show a moderate decline and recovery. SEQ, EDE, WE, MECA, and SSA exhibited the most serious disruptions.

Fig. B2 (b) shows that all inter-regional trade volume. All inter-regional trade volume involving EAQ, DA, and APQ exhibited high resilience with the least disruptions, as well as strong and quick recovery and growth. Inter-regional trade involving ADVEC and EU experienced moderate disruptions and quick recovery and growth, whereas inter-regional trade between the rest low-income regions (e.g., SEQ, EDE) show the most serious disruptions.

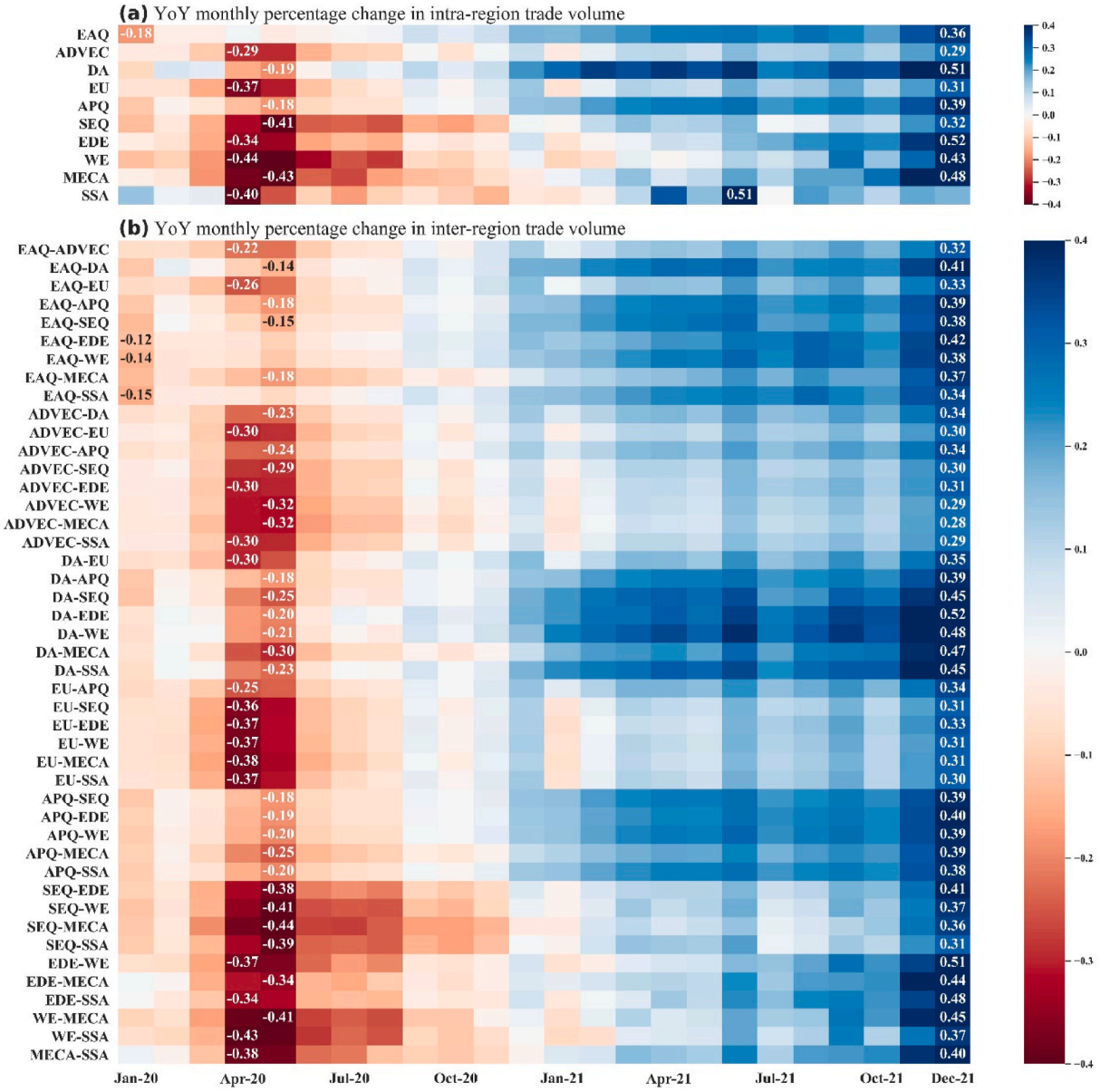

Fig. B.2. YoY monthly percentage change in both intra-region and intra-region trade volume. X-axis refers to months. In Fig. 7 (a), y-axis refers to regions sorted by the average GDP in 2019. In Fig. 7 (b), y-axis refers to the pairs of two regions. Those pairs are sorted by the average GDP from the large to the small by the first region, followed by the second region. The color scheme from red to blue indicates decline to growth of intra-region trade volume.

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