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# The impact of the COVID-19 pandemic on global trade-embodied carbon emissions

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ABSTRACT

We evaluate the response of global supply chains to carbon emissions through compiling multi-regional input-output (MRIO) models for import and export shocks in 14 countries/territories dominated by the COVID-19 crisis. Instead of traditional production-based inventories, we achieve $CO_2$ emissions inventories based on intermediate inputs and final consumption to analyze the connected environmental impacts. In addition, we adopt the available data up to date to construct inventories of carbon emissions involved in imports and exports from different sectors. The results show that global carbon emissions could be decreased by 6.01% during the COVID-19, while export carbon emissions remained basically unchanged. As a result, imported carbon emissions fell by 5.2%, with the energy products sector most affected by the pandemic. Transport sector witnessed 18.42% carbon emission reduction. The impact of developing countries with a large proportion of resource-based industries is comparatively higher than that of developed countries with the technological advantage. International trade plays a crucial role in the choice of supply chain partners to control carbon emissions. Building a sustainable supply chain and reducing the "trade carbon deficit" between countries/regions requires the coordination of all departments of each country/region to promote the trade of energy-saving products, environmental protection services and environmental services.

## 1. Introduction

Worldwide, a blockade is one of the prevailing approaches to control the spread of COVID-19 (Aum et al., 2021; Bank, 2020; Lu et al., 2021). The most recent blockades in some countries/regions (Gao et al., 2022) directly stemmed from the large-scale outbreak of the new COVID-19 variant virus "Omicron" in South Africa (Pulliam et al., 2021). Depending on the length of period and scalability, lockdowns may cause multiple influences, such as the psychological impact (Prati and Mancini, 2021), mental health issues (Ferwana and Varshney, 2021), diet and physical activity changes (Elisabeth et al., 2021), increased inequity (Bavli et al., 2020; Tabner, 2020), layoffs (Aum et al., 2021), shocks on income distribution and the food security (Arndt et al., 2020).

The impairment of the COVID-19 pandemic toward economic activities has a far-reaching impact. The impact on the global economy includes many manifestations, such as a reduction in gross domestic production (GDP) (Caselli et al., 2020), reduction in consumption (Lenzen et al., 2020), disruptions in the food supply chain (Khan et al., 2021; Singh et al., 2021), sharply decreased agricultural commodity prices (Elleby et al., 2020), panic consumption (Cariappa et al., 2021), multi-sector disequilibrium with buyer-seller relations between agents (Mandel and Veetil, 2020), job losses (Aum et al., 2021), firm exposure and value discount (Ding et al., 2022), fluctuations in stock prices (Davis et al., 2021), and the unstable cryptocurrency market (Rubbaniy et al., 2021). Some studies show that lockdowns may be associated with a 10–15% drop in local economic activity (Asahi et al., 2021), and the effect is proportional to the population under lockdown.

The COVID-19 pandemic continues, and the damage is far from what we are aware of now. Other than public health hazards and economic shocks, one big and often overlooked issue is the long-term and indirect impact of COVID-19 on urban and social sustainability, which is brought about by non-pharmaceutical interventions, such as lockdowns (Venter et al., 2020), social distancing, working place or school closures (Asahi et al., 2021; Gupta et al., 2020) in different countries and regions, emphasizing the challenge of addressing unsustainable global patterns in the nexus of socio-economy and environment (Lenzen et al., 2020). With respects of the impact on the sustainable development of cities and society, the supply chain plays a vital role, as it connects the two ends for production and consumption, which involves almost all aspects of social

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**Nomenclatures**

| | |
|---|---|
| vdfm | Domestic firm purchases |
| vdpm | Domestic household purchases |
| vdgm | Domestic government purchase |
| vdkm | Domestic investment purchase |
| vst | Export of international transport service |
| vxmd | Bilateral export |
| vom | Total output |
| vifm | Import firm purchase |
| vipm | Import household purchase |
| vigm | Import government purchase |
| vikm | Import investment purchase |
| vims | Total import |
| i, j | Sector |
| r, s | Region |
| X | Total output of column vectors of each department |
| Y | Final use of column vectors |
| I | Identity matrix |
| A | Block matrix |
| $CO_2$ | Carbon dioxide emissions from energy use |
| FC | Fuel consumption |
| CC | Conversion coefficient |
| CST | Ratio of carbon stored of energy |
| EF | Emission factor |
| FOC | Fraction of carbon oxidized of energy |
| E | Carbon emissions embodied in imports or exports |
| P | Population |
| Q | GDP value of imports or exports per capita |
| Te | Technological development level |
| ΔE | Difference between the carbon emissions embodied in exports or imports |
| w | Weight of social influences |

development, such as urban infrastructure, industrial structure, social contexts, and economy. Among them, the relevance of the supply chains to the environment has received increasing attention, for instance, the embodied carbon emissions of global supply chain (Wang, Y. et al., 2021), linking socioeconomic and environmental factors. In recent years, climate change ascribed to supply chains has imposed stricter requirements on its management (Correia et al., 2021) and technological improvements (Sayarshad, 2022). This issue becomes a top concern because it affects the way people live, the products they buy and the way they work.

In the current supply chain under the impact of COVID-19, however, the variation of carbon emissions has not been carefully overviewed. Our reviews of the literature concerning environmental impacts of COVID-19 pandemic have shown mixed results. On one hand, recent studies during the COVID-19 pandemic indicate alleviations in air pollution (Kerimray et al., 2020; Le et al., 2020; Venter et al., 2020), the improvement of urban surface ecological status (Firozjaei et al., 2021), and a modest reduction in greenhouse gas emissions (Bertram et al., 2021; Han et al., 2021; Simpkins, 2020). On the other hand, increased plastic pollution (Silva et al., 2021) and the trajectory rebound in carbon intensity (Aktar et al., 2021; Ray et al., 2021; Wang, Q. et al., 2021) present an immediate challenge in the post-COVID-19 scenario.

Global socio-economic losses and environmental gains from the Coronavirus pandemic suggest the intrinsic link between economic and social dimensions (Lenzen et al., 2020). Due to the socio-economic characteristics of most control measures and the suddenness of implementation, environmental effects lag the socio-economy shocks, which may not be instantly noticed. Especially within the large-scale ecosystem, it is difficult to accurately examine the relevant influences facing regional variability of these measures, the original economy shapes, and social infrastructures. On top of it, economic shocks spread through international supply chains (Giammetti et al., 2020; Guan et al., 2020; Inoue et al., 2021; Sanguinet et al., 2021; Yu et al., 2022). As such, the position of certain industrial sectors or countries/regions in the supply chain, the lockdown status of other sectors/regions serving their demand and supply, and the substitutability of suppliers, are vital links in determining the propagation effect in the global supply chain (Inoue et al., 2021).

Since the COVID-19 has not really ended, we adopted GTAP-MRIO to simulate the impact of the COVID-19 on various sectors in the short term. We demonstrated the impact of COVID-19 from an environmental and economic perspective for a sustainable society, estimating changes in $CO_2$ by studying changes in industry imports and exports for each country/region, as well as changes in production and consumption between countries/regions in the supply chain in order to highlight the current situation in regions affected by COVID-19 and analyze the impact of COVID-19 on the environment and supply chain sustainability. We have hereby reviewed the international trading activities during the COVID-19 pandemic for the whole year 2020 as compared to 2019, including interferences from the regional policies such as lockdown periods and scopes, the national GDP performances, and the labor market changes, to study their interaction with the earth system. Indeed, the complete presentation of those potential results under the influence of COVID-19 is a matter of time. The duration of specific measures (e.g., lockdowns) in multiple countries and regions, in conjunction with the dynamics of economic production and consumption, and industrial structure adjustments, has been reconciled to Global Trade Analysis Project (GTAP) v10 Data Base for integrated environmental impact assessment – with a specific focus on the supply chain of carbon emissions. The study will demonstrate the ripple effect of COVID-19, thus proving that the fragile performance of the international supply chains may not be all bad from an environmental perspective.

## 2. Methodology

The GTAP is based on a comprehensive multi-country input-output database (Siriwardana and Yang, 2008). The basic database is GTAP's most important resource, detailing the production of related products within each region and the international trade between regions (Van Ha et al., 2017). GTAP architecture takes production, consumption, and government expenditure of individual countries and regions as sub-models, and depicts trade relations of various countries with quantitative data after input data and conversion of various parameter coefficients (Siddig et al., 2016). Finally, the models can be linked together to form a multi-country and multi-sector equilibrium model. The model can be used to simulate changes in domestic production, social welfare, employment, imports, and exports of target countries or regions before the implementation of trade policies, and to plan corresponding measures based on this analysis (Avetisyan and Hertel, 2021; Dissanayake et al., 2020; Walmsley et al., 2018).

Influenced by the COVID-19 outbreak, the global economy is facing a severe recession, the global supply chain and therefore suffering a severe stroke, so we are based on the global multi-regional input-output model, the application in countries/regions of import and export shocks by the COVID-19 crisis, to evaluate the response to the global supply chain carbon emissions. For the convenience of research, we classify and adjust the 141 countries and 65 sectors in GTAP database according to the geographical location and the international status. Taken the population and trade volume into consideration, United States, United Kingdom, China, and India were counted separately to avoid driving up the total values of each area. Several small countries are categorized in the rest of their respective regions. The aggregation of the 14 countries/regions and sectors is shown in Table 1 and Table 2.

**GTAP database update.** For GTAP to update the underlying database, effective changes to endogenous variables must begin with changes to exogenous variables. Basic macroeconomic variables are recognized as important references affecting national economy and bilateral trade. Therefore, we use the GTAP self-equilibrium model to update the trade balance relationship within its database to 2019 by updating and changing exogenous macroeconomic variables. Since the base period of the GTAP database is 5 years, the current database is 2014. Therefore, to update the database, we update the data in the database according to the five factors of production of macroeconomic aggregate: population, GDP, skilled labor force, unskilled labour force and capital stock. These five factors of production not only affect each other but also the key factors affecting the economic growth of the country/region. For example, as an input factor of production, the increase in population is finally implemented into the increase of the quantity and quality of the labor force population, thus affecting economic growth. At the same time, for the capital stock, the change of capital stock will also lead to a change in the labor force, the availability of natural resources will also change, thus affecting the aggregate demand factors, and consumer demand preferences will also change accordingly. Among them, population data mainly comes from the World Bank, GDP data update comes from the World Bank, labor force growth rate comes from the World Labor Organization, and capital stock growth rate comes from the World Bank. The macro variables required by each region/country to implement database updates are shown in Table 3.

**GTAP model impact scenario to describe the impact of COVID-19.** In December 2019, COVID-19 broke out and rapidly spread to most countries in the world, so the continued spread of the epidemic has a huge economic impact on global value chains, trade, and transport (Chen and Mao, 2020; Cui et al., 2021; Free and Hecimovic, 2021). To simulate the impact of COVID-19 on each country's economy, reflecting its impact on labour constraints, trade and GDP, we set three variable values and added 14 country/regional impact shocks to run GTAP based on changes in these three shock values(Fonseca and Azevedo, 2020; Hayakawa and Mukunoki, 2021; Maffioli, 2020; Verschuur et al., 2021; Zeshan, 2020). The impact degree of each variable is shown in Table 4.

Labor restriction. Unemployment is a key factor in analyzing the impact of COVID-19, as labor constraints could have knock-on effects in other economies (Blustein et al., 2020). In the context of the COVID-19 pandemic, some businesses have been forced to shut down their operations, resulting in their employees unemployed or unable to work (Su et al., 2021). Therefore, considering the impact of the epidemic on economic activities, the unemployment rate is selected as one of the key influential factors of the epidemic.

**Table 1**
Regional aggregation in GTAP.

| Region | Region description |
|---|---|
| US | |
| UK | |
| China (mainland) | |
| India | |
| Oceania | Australia, New Zealand |
| East Asia | Hong Kong, Japan, Korea, Mongolia, Taiwan, Brunei Darussalam, Rest of EA |
| Southeast Asia | Cambodia, Indonesia, Lao People's Democratic Re, Malaysia, Philippines, Singapore, Thailand, Viet Nam, Rest of SEA |
| South Asia | Bangladesh, India, Nepal, Pakistan, Sri Lanka, Rest of SA |
| North America | Canada, Mexico, Rest of NA |
| Latin America | Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Venezuela, Costa Rica, Guatemala, Honduras, Nicaragua, Panama, EI Salvador, Dominican Re, Jamaica, Puerto Rico, Trinidad and Tobago, Caribbean, Rest of Sam and Central America |
| European | Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Re, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden |
| Middle East and North Africa | Bahrain, Iran, Israel, Jorden, Kuwait, Oman, Qatar, Saudi Arabia, Turkey, United Arab Emirates, Egypt, Morocco, Tunisia, Rest of WA and NAf |
| Sub-Saharan Africa | Benin, Burkina Faso, Cameroon, Cote d'lvoire, Ghana, Guinea, Nigeria, Senegal, Togo, Central Africa, South Central Africa, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, Tanzania, Uganda, Zambia, Zimbabwe, Botswana, Namibia, South Africa, Rest of WAf and EAf |
| Rest of World | Switzerland, Norway, Albania, Belarus, Russian Federation, Ukraine, Kazakhstan, Kyrgyzstan, Tajikistan, Armenia, Azerbaijan, Georgia, Rest of European, EFTA and former Soviet Union |

**Table 2**
Sectoral aggregation in GTAP.

| Sector | Sector description |
|---|---|
| Grains and Crops | Paddy rice, Wheat, Cereal grains, Vegetables, Fruits, Nuts, Oil seeds, Sugar cane, Sugar beet, Plant-based fibers, Crops, Processed rice |
| Livestock and Meat products | Bovine cattle, Sheep and goats, Animal products, Raw milk, Wool, Silk-worm cocoons, Bovine meat products, Meat products |
| Mining and Extraction | Forestry, Fishing, Coal, Oil, Gas, Minerals |
| Processed Food | Vegetable oils and fats, Dairy products, Sugar, Food products, Beverages and tobacco products |
| Textiles and Clothing | Textiles, Wearing apparel |
| Light Manufacturing | Leather products, Wood products, Paper products, Publishing, Metal products, Motor vehicles and parts, Transport equipment, Manufactures |
| Heavy Manufacturing | Petroleum, Coal products. Chemical products, Basic pharmaceutical products, Rubber and plastic products, Mineral products, Ferrous metals, Metals, Computer, Electronic and optic, Electrical equipment, Machinery and equipment |
| Utilities and Construction | Electricity, Gas manufacture and distribution, Water, Construction |
| Transport and Communication | Trade, Accommodation, Food and service, Transport, Water transport, Air transport, Warehousing and support activities, Communication |
| Other Services | Financial services, Insurance, Real estate activities, Business services, Recreational and other service, Public Administration, Education, Human health and social work, Dwellings |

**Table 3**
Macroeconomic variables used for dynamic recursion in 2014–2019 (Database: World Bank, FAO, OECD).

| Region | Increasing rate (%) | | | | |
|---|---|---|---|---|---|
| | population | GDP | Skilled Labour | Unskilled Labour | Capital stocks |
| US | 3.26 | 22.29 | 10.65 | 21.77 | 11.05 |
| UK | 3.22 | −7.8 | 26.5 | 27.29 | 11.88 |
| China (mainland) | 2.44 | 36.41 | 23.13 | 22.97 | 45.62 |
| India | 5.47 | 41.54 | 23.64 | 20.25 | 27.99 |
| Oceania | 6.47 | −4.7 | 14.27 | 24.62 | 12.52 |
| East Asia | 0.08 | 6.16 | 20.78 | 24.01 | 11.55 |
| Southeast Asia | 5.59 | 24.59 | 32.87 | 28.86 | 25.59 |
| South Asia | 8.31 | 26.86 | 14.33 | 21.09 | 21.55 |
| North America | 5.75 | −3.85 | 30.72 | 21.78 | 15.94 |
| Latin America | 6.65 | −18.2 | 18.28 | 21.79 | 19.04 |
| European | 0.32 | −1.15 | 32.45 | 26.39 | 8.96 |
| Middle East and North Africa | 10 | 0.12 | 28.26 | 24.02 | 22.61 |
| Sub-Saharan Africa | 14.11 | −1.09 | 19.1 | 18.38 | 25.61 |
| Rest of World | 2.05 | −3.63 | 20.5 | 24.39 | 14.04 |

**Table 4**
Shock variables of COVID-19 in GTAP.

| Region | Change rate (%) | | |
|---|---|---|---|
| | Trade volume | Unemployment rate | GDP |
| US | −10.4 | −8.31 | −3.64 |
| UK | −7.9 | −4.34 | −9.69 |
| China (mainland) | 2.4 | −5 | 2.35 |
| India | −11.6 | −7.11 | −7.25 |
| Oceania | −3.5 | −5.58 | 0.22 |
| East Asia | −14.2 | −4.93 | −3.60 |
| Southeast Asia | 0.95 | −4.3 | −3.92 |
| South Asia | −13.8 | −6.63 | −2.38 |
| North America | −5.2 | −7.09 | −6.59 |
| Latin America | −9.1 | −10.28 | −6.12 |
| European | −7.9 | −7.37 | −5.97 |
| Middle East and North Africa | −9.7 | −11.7 | −4.69 |
| Sub-Saharan Africa | −7.7 | −6.63 | −2.08 |
| Rest of World | −10.8 | −6.47 | −3.06 |

Trade volume. The outbreak has a direct impact on exports, the impact is mainly manifested in two aspects, the various countries/regions for the outbreak of panic, in countries with outbreaks, take preventive measures, these measures cannot avoid a certain impact on exports, may in the short term increase the cost of transportation of export commodities, etc.(Guo et al., 2020). As a result, the competitiveness of export goods has declined. The control measures taken by the epidemic countries will also affect the production and business activities of enterprises, and the production of some export enterprises will be interrupted, which will have an impact on all domestic industries (Lin and Zhang, 2020). Therefore, the total amount of exports is also selected as the main factor influencing the variables to analyze the degree of country/region dependence on the supply chain.

GDP. COVID-19 not only has a great impact on export but also has a certain impact on domestic production(Keogh-Brown et al., 2020). COVID-19 prevents people from going out for shopping, tourism, consumption, and investment, which leads to a decrease in economic activities and thus a decrease in the GDP of each country(de la Fuente-Mella et al., 2021). Therefore, GDP is selected as one of the shock variables to compare the changes of domestic production and consumption before and during COVID-19.

**Construct Multi Regional Input-output Tables**. GTAP is most relevant to this paper for the database, which is based on the national input-output table, trade, macroeconomic, and protection data bureau, and thus provides the data for quantitative analysis for the construction of the MRIO table(Giljum et al., 2019). Table 5 lists the GTAP variables necessary to construct an MRIOT, although the database does include more variables than presented here. The convention we use here is that the indices *i, j* represent sectors, while *r, s* represent regions. Due to the combination of many data that may cause conflicts in the GTAP database, we need the correct combination of data when constructing the MRIO table to form each seed matrix in the MRIO table(Andrew and Peters, 2013).

**Table 5**
The GTAP data used to construct or check the MRIOT.

| GTAP | IOT | Description |
|---|---|---|
| **Domestic data** | | |
| $vdfm_{ij}^r$ | $Z^{rr}$ | Domestic firm purchases of *i* by *j* in region *r* |
| $vdpm_i^r$ | | Domestic household purchases of *i* in region *r* |
| $vdgm_i^r$ | | Domestic government purchase of *i* in region *r* |
| $vdkm_i^r$ | | Domestic investment purchase of *i* in region *r* (in GTAP this is an extra column in *vdfm*) |
| $vdpm_i^r + vdgm_i^r + vdkm_i^r$ | $y^{rr}$ | Domestic purchase of *i* in region *r* |
| $vst_k^r$ | $t^r$ | Export of international transport service *k* from region *r* |
| $vxmd_i^{rs}$ | $e^{rs}$ | Export of *i* from region *r* to region *s* (valued in market prices of *r*) |
| $vom_i^r$ | $x^r$ | Total output of *i* in region *r* |
| **Import data** | | |
| $vifm_{ij}^s$ | $Z^m$ | Import firm purchase of *i* by *j* in region *s* |
| $vipm_i^s$ | | Import household purchase of *i* in region *s* |
| $vigm_i^s$ | | Import government purchase of *i* in region *s* |
| $vikm_i^s$ | | Import investment purchase of *i* in region *s* (in GTAP this is actually as an extra column in *vifm*) |
| $vipm_i^s + vigm_i^s + viim_i^s$ | $y^m$ | Import purchase of *i* in region *s* |
| $vim_i^s$ | | Total import of *i* into region *s* |

The GTAP variable is connected by several IO relationships. The equation of domestic production in the region is shown in Eq. (1).

$$vom_i^r = \sum_j vdfm_{ij}^r + vdpm_i^r + vdgm_i^r + vdkm_i^r + vst_i^r + \sum_s vxmd_i^{rs} \tag{1}$$

A similar equilibrium in Eq. (2) exists for imports produced by region and imports produced by sector.

$$vim_i^s = \sum_r vims_i^{rs} = \sum_j vifm_{ij}^s + vipm_i^s + vigm_i^s + vikm_i^s \tag{2}$$

We construct the MRIOT in the tradition of IOA. It is also possible to use a mass-balance approach based on the GTAP balances. The MRIO model uses a linear equation system to describe the economic linkages between different regions and sectors. The most basic input-output relationship is Eq. (3):

$$X = (I - A)^{-1} Y \tag{3}$$

where, *X* represents the total output of column vectors of each department, *I* is the identity matrix, and *Y* represents the final use of column vectors. *A* is the block matrix, the specific input-output analysis can be expressed as Eq. (4):

$$\begin{pmatrix} X^1 \\ X^2 \\ \vdots \\ X^m \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & \cdots & A_{1m} \\ A_{21} & A_{22} & \cdots & A_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ A_{m1} & A_{m2} & \cdots & A_{mm} \end{pmatrix} \begin{pmatrix} x^1 \\ x^2 \\ \vdots \\ x^m \end{pmatrix} + \sum_s \begin{pmatrix} y^{1r} \\ y^{2r} \\ \vdots \\ y^{mr} \end{pmatrix} \tag{4}$$

where $x^m$ is a vector of total economic output of each sector in region *r*, $y^{qr}$ is a vector of each sector's output produced in region *q* and consumed in region *r*, and $A^{qr}$ is a normalized matrix of intermediate consumption where columns reflect the input from sectors in region *q* required to produce one unit of output from each sector in region *r*. As opposed to input–output models that allocate emissions according to bilateral trade, here each submatrix $A^{qr}$ is constructed by splitting bilateral trade data into components satisfying intermediate and final demand. This is done by using the input–output relationships of imports to region *r*, distributed according to the share of all imports to region *r* made up of exports from *q*.

Based on the above construction methods, we take 2019 database after recursion and the database after simulated shock as the basis for MRIO construction. Through the above arrangement and combination, we construct two tables of value-input-output analysis based on production-consumption. Each input-output analysis includes the volume of trade value of domestic production and use as well as import and export.

**Carbon dioxide emissions inventory.** There are two main steps to construct an inventory of carbon emissions based on intermediate use, final consumption, and total output (Owen et al., 2014). The first step is to calculate national and regional carbon emissions from energy-burning according to the guidelines provided by Lee (2008). The GTAP10 database includes six energy products, coal, crude oil, natural gas, petroleum products, electricity, and gas distribution (EGDT). Before calculating carbon emissions from each sector of energy use in countries and regions, we need to make two revisions to the raw data (Lee, 2008). One revision is to separate energy used for combustion from energy used as a feedstock since some natural gas and oil do not emit $CO_2$ when used as feedstock. Therefore, we adopted Huey-Lin Lee the raw material ratio provided is calculated. The second revision is based on the fact that several sectors use energy for other activities that do not generate $CO_2$. After revising the data on fuel use, we calculated the carbon emissions generated by energy products in various industries in each country and region in 2014 through Eq. (5).

$$CO2_{ijr} = \left( FC_{ijr} \times CC_i \times \left(1 - CST_{ijr}\right) \times EF_i \times FOC_i \times \left(\frac{44}{12}\right)\right) \Big/ 1000 \quad (5)$$

where, $CO_{2ijr}$ is carbon emissions (kt) from energy commodity *i* used by sector *j* of region *r*; $FC_{ijr}$ is fuel consumption (1000 tons of oil equivalent, or 1000 toe) of energy commodity *i* by sector *j* of region *r*; $CC_i$ is conversion coefficient (tera joule per 1000 toe) of energy commodity *i*; $CST_{ijr}$ is ratio of carbon stored of energy commodity *i* used by sector *j* of region *r*; $EF_i$ is emission factor (tones Carbon per tera joule, or tC/TJ) of energy commodity *i*; and $FOC_i$ is fraction of carbon oxidized of energy commodity *i*.

Particularly, to calculate the carbon emissions generated by the consumption of electric energy by various departments, this paper adopts the method of converting electric power into standard coal, with a conversion coefficient of 0.1229 kg/kWh and 2.763 kg/kg. This allows the calculation of carbon emissions from each sector's electricity consumption.

The second step is to export the trade and demand data provided in GTAP10 according to Peters et al. (2011). The proposed method forms the data into a matrix style to construct the input-output tables of each region and department, and to obtain the list of intermediate use, final consumption, and total carbon emissions. We calculated the carbon emission coefficient of each region and sector by calculating the $CO_2$ and input-output list of each region and sector in 2014. Then, the carbon emission intensity of 14 countries/regions in GTAP is updated to 2019 according to the change law of the carbon emission coefficient from 2014 to 2019.

**Conversion between value and carbon dioxide emissions.** After updating and influencing the database, the input-output table of the value volume in 2019 and after the epidemic impact was constructed according to the above method. Then, we integrated the values of intermediate use, final consumption, total output, trade import and export and carbon emission coefficient of each country and region into the improved MRIO model, so that the carbon emission trade links between each country and region were included in the model.

**Index decomposition analysis of emissions embodied in trade.** For socio-economic phenomena, there exist many complex economies that cannot be directly added or compared. To reflect and study the direction and degree of carbon emission changes caused by economic changes, it is necessary to analyze and measure the influence of various factors on the overall change of social economic phenomenon through index decomposition analysis. In our study, we analyzed the degree of influence of three major social factors on economic changes to gain a better understanding of the specific causes of changes in carbon dioxide emissions between countries/regions. The index decomposition of trade embodied carbon emissions is given by Eq. (6),

$$\mathrm{E} = \sum_i E_i = \sum_i P \frac{Q_i}{P} \frac{E_i}{Q_i} = \sum_I PQ_{ip} Te_i \quad (6)$$

where E describes carbon emissions embodied in imports or exports, P refers to the population, Q is the GDP value of imports or exports per capita and Te refers to the technological development level which is based on the IPAT identity, where IPAT stands for the human impact (I) on the environment as a function of three factors: population (P), affluence (A), and technology (T), the ratio of carbon emissions per capita to its GDP per capita of a region symbolizes its technology level (Nebojsa Nakićenović, 2000). The lower the emission-GDP ratio, the higher the technology level. Thus, the factors contributing to a net increment because of COVID-19 in embodied emissions can be expressed based on the logarithmic mean divisia index (LMDI) approach (additive from) as:

$$\Delta \mathrm{E} = E^{COVID-19} - E^{19} = \Delta E_{pop} + \Delta E_{GDP} + \Delta E_{tec} \quad (7)$$

where ΔE is the difference between the carbon emissions embodied in exports or imports during COVID-19 ($E^{COVID-19}$) and the carbon emissions embodied in those in 2019 ($E^{19}$); $\Delta E_{pop}$, $\Delta E_{GDP}$ and $\Delta E_{tec}$ refer to the population and economic scale effect and technology scientific progress degree effect, respectively, where $\Delta E_{pop}$, $\Delta E_{GDP}$ and $\Delta E_{tec}$ are expressed as Eqs. (8)–(11), respectively:

$$\Delta E_{pop} = \sum_i w_i \ln\left(\frac{P_i^t}{P_i^0}\right) \quad (8)$$

$$\Delta E_{GDP} = \sum_i w_i \ln\left(\frac{Q_i^t}{Q_i^0}\right) \quad (9)$$

$$\Delta E_{tec} = \sum_i w_i \ln\left(\frac{Te_i^t}{Te_i^0}\right) \quad (10)$$

$$w_i = \frac{E_i^t - E_i^0}{\ln E_i^t - \ln E_i^0} \quad (11)$$

$P^t$, $Q^t$ and $Te^t$ are the population, GDP per capital and technological development level of exports or imports during COVID-19. $P^0$, $Q^0$ and $Te^0$ are those in 2019.

**Limitation.** Due to the limited availability of data, the data in the GTAP database is from 2014, and we updated the database to 2019 through the changes in major production factors. The data of 2019 obtained through the recursive method will inevitably have some errors from the actual data of 2019. In view of the calculation results, we compared the existing national and regional carbon emission data with the carbon emission data calculated by GTAP. Since the division between regions has a certain subjective initiative, we compared the carbon emissions of countries/regions with relatively consistent division to verify our calculation results. In addition, we note that changes in the shock and carbon emission coefficients for each country/region may involve different sectors. But in our study, these small differences could not be distinguished by the impact of each sector. Meanwhile, in the basic database we found, we did not find a complete and detailed sector carbon intensity updated to 2019.We, therefore, use the change in shocks for each country/region as a measure of the change it has experienced during COVID-19.

## 3. Results

In 2019, the total output carbon emissions of 14 countries/regions reached 39616.26 Mt $CO_2$-eq. Since the outbreak of COVID-19, total global carbon emissions have decreased by 6.01% during the COVID-19. Fig. 1 shows the relative flow and distribution of carbon emissions across 14 countries/regions before and during the COVID-19 outbreak. In terms of global trade relations, carbon emissions from countries that play significant roles in international trade around the world have been most affected by COVID-19 (Fig. 1a). As a major trading nation and an important part of the international industrial chain, China's carbon emissions from exports have increased overall, among which the carbon emissions from exports to the US have increased by 59.19%. However, China's exports to other countries showed varying degrees of decline in carbon dioxide emissions, so China's overall export carbon emissions only increased by 3.84%. At the beginning of epidemic prevention and control, China adopted a policy of lockdown and isolation (Chen et al., 2020), and the epidemic was basically under control. At the time, however, the US was still in the stage of an epidemic (Hanif et al., 2021). The US itself is the world's largest importer of $CO_2$, with imported

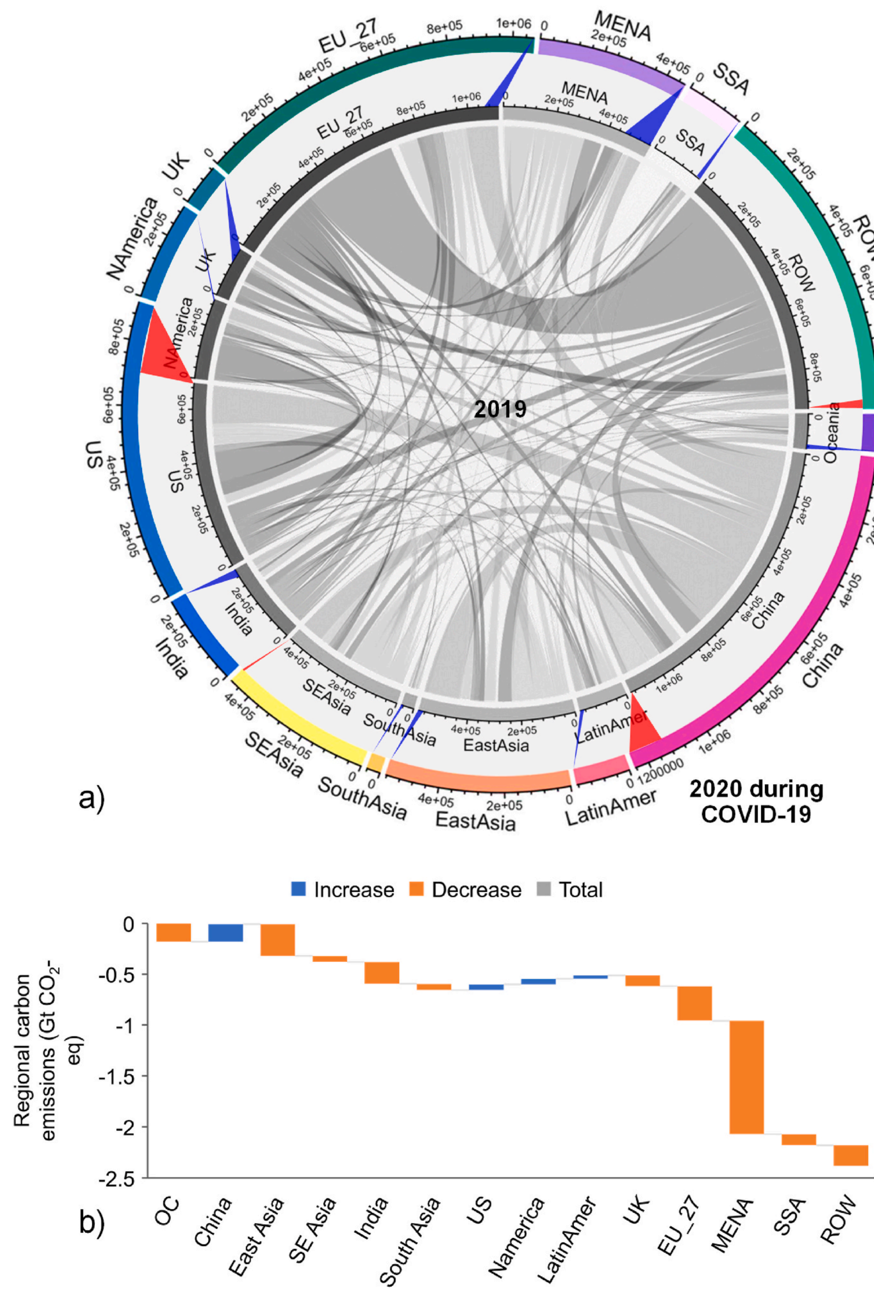


**Fig. 1.** a) comparison of carbon emissions from the supply chain between 2019 and the period of the COVID-19 pandemic (red and blue area refer to increased and decreased carbon emissions, respectively.), b) regional carbon emission changes between 2019 and the period of the COVID-19 pandemic. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

emissions rising fastest during the COVID-19 pandemic as American consumers who spend a lot of time at home snap up products made in other countries/regions. In addition, China's rapid economic recovery has made it a major source of imports to the US, leading to a sharp increase in imported carbon emissions. As a result, China's carbon exports to the US have continued their previous trend of high growth. During the COVID-19 pandemic, US residents began to buy telecommuting electronic equipment such as home computers with the largest increase in imports(Cohen and Rodgers, 2020), but the government restricted the export of various goods, so its export carbon emissions were relatively low. For the EU, another big economy, the outbreak of COVID-19 has been accompanied by Brexit, thus losing a relatively important trading partner, which led to the reduction of import and export trade between the EU and the UK. As a result, EU emissions to and from the UK are lower than in 2019. However, the supply shortage suffered by the EU itself makes Asian countries very advantageous to the EU's exports. Meanwhile, the EU's carbon emissions exported to China increased by 38.03%. It also suggests that the UK will lose some of its advantages in the EU market after Brexit and that the EU itself wants to increase access to consumer markets other than the UK.

At the national level, $CO_2$ emissions will be affected to varying degrees (Fig. 1b). Total carbon emissions decreased significantly in the Middle East and North Africa (31.55%), the United Kingdom (27.93%), Oceania (26.03%), South Asia (17.20%), East Asia (13.94%) and the European Union (11.25%). The decline in total $CO_2$ production in such countries is mainly due to the reduction in basic energy consumption as a direct result of the constraints on economic activity. For Latin America, North America and the US, total carbon emissions are rising instead. During the COVID-19 pandemic, the countries produce fewer goods and services and rely heavily on goods and services provided by other countries/regions, leading to an increase in carbon emissions in final consumption, which in turn leads to an increase in total carbon emissions produced. China's total carbon emissions increased by 1.71%, indicating that despite the indelible impact of the epidemic on the economy, the economy and carbon emissions quickly rebounded thanks to China's proactive epidemic prevention and control policies(Mei, 2020).

By analyzing the import and export trade of each sector in each country, we can observe the dependency of the countries/regions on the supply chain. As can be seen from Fig. 2, the change in export carbon emissions is relatively stable before and during the epidemic, and there is no significant increase or decrease in export carbon emissions. Some of these countries, such as China, the European Union and ROW, had seen slight increases in export carbon emissions, up 3.84%, 12.08% and 4.28% respectively (Fig. 2a). The increase in export emissions in China and ROW was mainly due to carbon emissions from the extractive sector, while carbon emissions from all other sectors declined (Fig. 2c and d). This shows that energy demand remains high, even with the impact of the pandemic. The COVID-19 pandemic has led to fewer mining workers and longer mining cycles, resulting in higher per capita carbon emissions. In order to meet the energy needs of other countries, its export carbon emissions increase significantly. In the case of the European Union, carbon emissions have increased in all sectors. The most obvious was the light industrial sector, which grew by 16.10%. This indicates that under the impact of the COVID-19 pandemic, carbon emissions from exports of labor-intensive products in the EU have increased instead, because carbon emissions per capita are gradually increasing under the situation of labor constraints due to the impact of the pandemic, so carbon emissions from exports of light industry have increased.

The COVID-19 pandemic, including the global lockdown, has led to a declination in exports from India and the Middle East and North Africa (Fig. 2a), with significant impacts on almost all sectors in these countries, with the agricultural sector particularly pronounced (Fig. 2c and

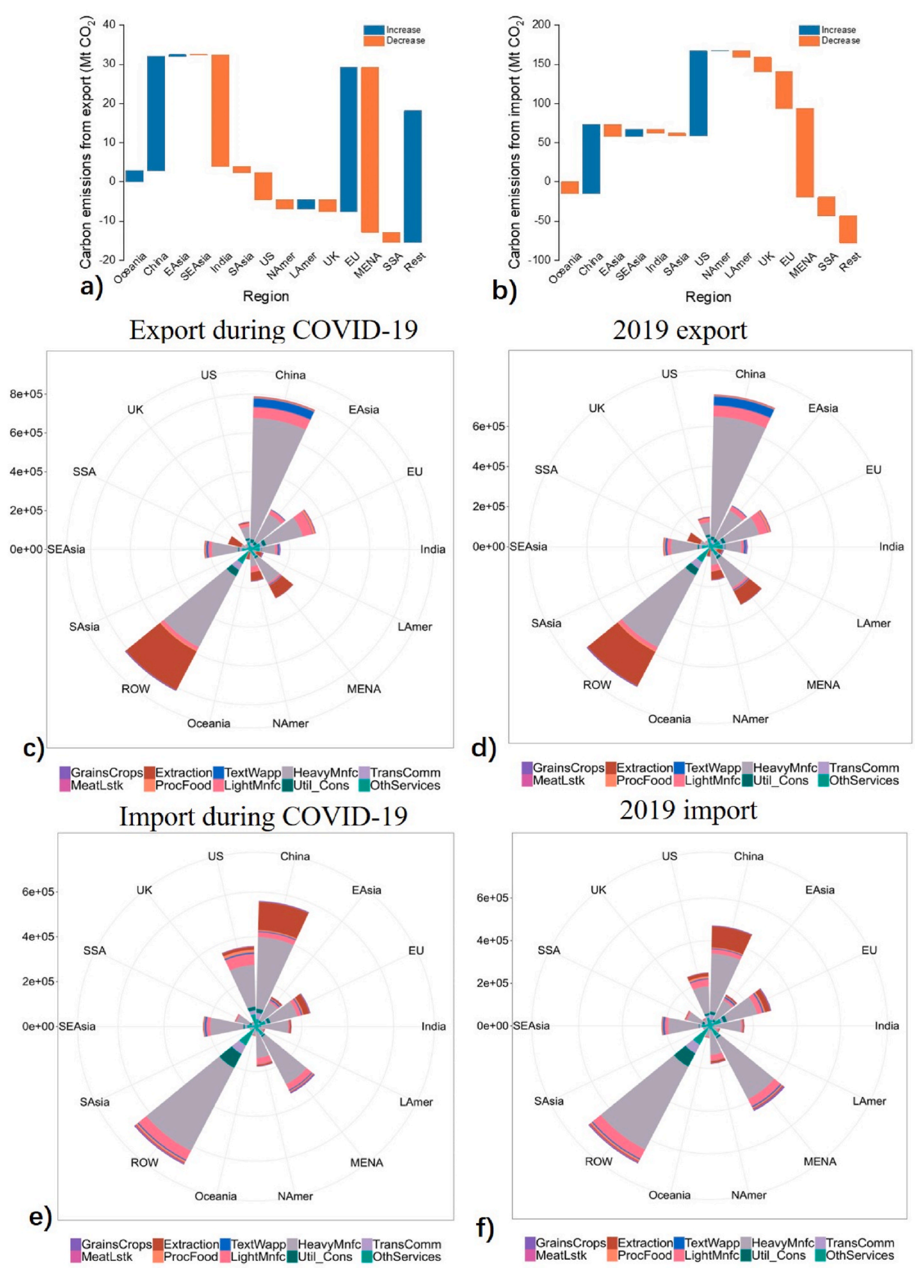


**Fig. 2.** Carbon emissions for global export(a), import(b) and sectors(c-f) in 2019 and during the COVID-19 pandemic.

d). The impact of COVID-19 on agricultural exports can be divided into supply and demand. As for the producing areas of agricultural products, the sudden outbreak of COVID-19 has affected the producing areas, missed the best harvest period of products, and made it difficult for employees to resume work, resulting in serious unsalable phenomenon (Ahmed and Memish, 2020). Transportation was blocked after the outbreak of the epidemic, which made many agricultural products deteriorate during storage and transportation, affecting their export (Gray, 2020). As a result, the export carbon emissions of these major agricultural exporters have been severely reduced (Coluccia et al., 2021). In the meantime, during social isolation measures to reduce transmission of the virus, total transport sector carbon emissions were reduced by 18.42%. The main reasons for this are twofold. On the one hand, the flow of passengers is limited by the need for social distancing. Another reason is that most traffic is at a standstill.

In terms of imported carbon, the amount of imported carbon fluctuated significantly before and during the COVID-19 pandemic (Fig. 2b). In the wake of the COVID-19 shock, total global imported carbon emissions have decreased. From the chart of total imported carbon emissions, the US had the largest increase in imported carbon emissions among all countries/regions, with an increase of 42.99%. Among them, public utilities and construction are the main industries leading to the increase of imported carbon emissions in the US, whose imported carbon emissions increased from 14 $MtCO_2$ eq to 23 $MtCO_2$ eq, which means that the US, as a developed country, has always paid attention to the management of public utilities, while the carbon emissions of public utilities have always depended on the superstructure (Fig. 2e and f). But the US economy has been hit hard by the COVID-19 pandemic. To maintain its economic level and residents' daily needs for water, electricity and gas, the US relies on importing related energy products from other countries(Fan et al., 2019). While total imported carbon emissions in the US were on the rise, imported carbon emissions from the mining industry fell by 19.80%, suggesting that the impact of COVID-19 has reduced demand for raw materials mined in the US. The same trend was observed in China and Southeast Asia, where carbon imports from utilities and construction increased by 32.35% and 23.57%, respectively. After utilities and construction, meat imports were the second biggest contributor to the increase in carbon emissions in China. This is due to China's need to import frozen meat and seafood products from other countries, and the African Swine fever outbreak during COVID-19 (Tucker et al., 2021; Wang et al., 2020) has also made pork imports from China riskier. Therefore, China needs to find other suppliers, so there are more opportunities for refrigerated vacuum-packed pork from other countries to be sold in China, and this kind of pork often contains more hidden carbon emissions than previous fresh meat, leading to the increase in the carbon emissions of China's meat imports.

SSA's imported carbon emissions, which were most affected by COVID-19, decreased by 20.24%. Because of the effect of the coronavirus, interrupted cross-border trade activities, including informal cross-border trade accounts for about a third of the total amount of African trade, limiting the spread of the flow the serious influence the SSA's trade and informal, whereas most of the world leads to import products production factory closed, so the region's biggest drop in imports of carbon emissions. In particular, the biggest import losses are in the food sector, as nearly two-thirds of African countries are net food importers, with low rates of food self-sufficiency and chronic food shortages. In 2020, Africa itself suffered from severe natural disasters, exacerbated by the COVID-19 pandemic. In addition, a series of policies such as border closures and closures have disrupted the operation of the food supply chain to some extent, resulting in reduced consumer demand in SSA areas. Coupled with a weaker currency, the price of imported goods has risen accordingly. As a result, carbon emissions from food imports were reduced by 24.83%. Thus, in response to the impact of COVID-19 on food security, African governments have cut business taxes to stimulate domestic food production and reduced income taxes to boost household incomes(Nkamleu, 2021). Energy-intensive regions such as the Middle East and North Africa have also been particularly badly affected. We all know that the oil and gas industry is the biggest driver of carbon emissions, but the energy extraction industry is also losing a lot of imported carbon emissions as the COVID-19 pandemic has forced workers and machinery to sit idle (Koca and Genc, 2020).

In short, from the national level, China, the EU and the US can help maintain the balance of supply chain. At the same time, India, the Middle East and North Africa are highly dependent on the supply chain, because once the supply chain of these countries is broken (Fan et al., 2022), it will affect all aspects of the country/region. By sector, the utilities of US and SSA's agricultural sector are more uncertain, and are relatively vulnerable to supply chain disruptions.

When we further analyze the ratio of imports and exports by sector and carbon emissions by sector to total output emissions, we can analyze the regional heterogeneity of COVID-19 on the industrial structure of different countries. Fig. 3 shows the share of carbon dioxide emissions from imports, exports, and industries in total $CO_2$ emission under the COVID-19 pandemic. The proportion of carbon emission of imports and exports in most regions remains volatile or moderately decreases due to offsetting effects of slowing globalization and national development (Fig. 3a). Even though the carbon emission of gross output is generally reduced, the volumes of exports are still shrinking except for an apparent growth in EU, SEA, and Oceania (SI). Correspondingly, their share of export carbon emissions has risen due to the stable trading partners and markets, however, the causes of carbon emissions of increased exports vary. The ratios of carbon emissions of food, light industry and service products in the EU have increased, while the output of energy products in SEA is skewed (Fig. 3c, g & i), which is directly related to the indigenous type of industry (Felker, 2003). An exceptional case is Oceania, whose carbon emissions of exports share add ~50%, as the result of superimposed effects of leading industries and demand for basic goods under COVID-19 (Fig. 3e, f & g). Transport was disrupted in half the regions (Fig. 3k), while the energy gap was widened (Fig. 3c).

China and the US, as major carbon emitters, that of gross output, are still maintaining certain growth trends. Similarly, their export carbon emissions rose steadily. As it happens, China and the US are examples of two ways of responding to COVID-19. The former is the gradual resumption of the industry after the strict blockade, which can be reflected in the subsequent increase in the output of medical resources. The latter is to sustain economic and social operation as the main goal, trying to establish a complete supply chain, where light industry and heavy industry carbon emission has a rising trend. Yet labor-intensive industries-oriented areas, especially SSAF and India (Hilson and Ackah-Baidoo, 2011; Pio, 2016), suffer from contact limits and shorter working hours (Fig. 3a and b). The pandemic has exacerbated the polarization, with developing countries losing their labor advantage and consuming huge amounts of goods to keep their residents alive. For food, textiles and other materials import growth are particularly obvious (Fig. 3e, g & h). Faced with the dual needs of increasing unemployed people and instant communication, the government usually releases infrastructure plans to relieve people's living pressure to a certain extent. Consequently, construction and transportation have increased in different proportions, except for US and UK (Zhang et al., 2020) enacted monetary policy (Fig. 3j).

In theory, during the epidemic, regional strategic reserves are of great significance, primarily reflected in the food, textiles, and light industrial supplies. Part of domestic with a more complete supply chain system of the regions normally contracts export aimed to give priority to local consumption. Other developed countries with enough skilled workers and manufacturing technology reorganize the lifeline industry chain, such as much-needed protective goods. However, Oceania, which is famous for advanced agriculture and animal husbandry exports quite food quantities to other developing countries with a large population base and complex geographical conditions. On a macro level, labor-oriented industries declined significantly overall due to contact restrictions, but the demand for communications and related construction

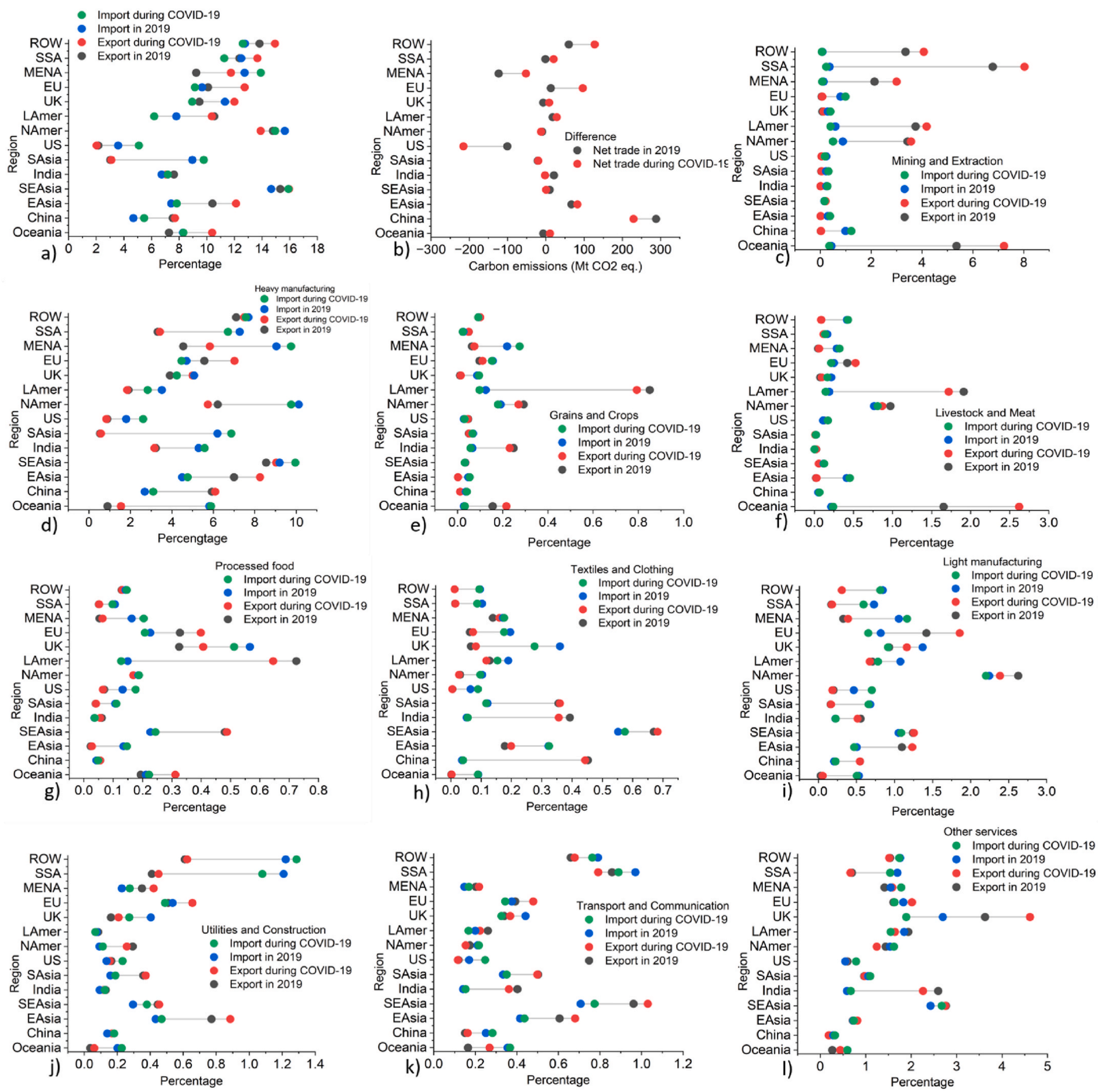


**Fig. 3.** The percentage of total carbon emissions by import and export (a), net trade(b) and various sectors(c-l) from the supply chain influenced during the COVID-19 pandemic.

has become inevitably immediate. The lack of raw materials and parts makes the latter part of the chain unsustainable.

In Fig. 4, we analyze the differences in industry and carbon emission coefficient in 14 countries/regions, and compare the differences in the contribution of social factors to carbon emission. The carbon emission coefficient of each industry in each country is compared (Fig. 4a). Vertically, the carbon emission coefficient of industry and service industry in each country/region is significantly higher than that of agriculture and other sectors. Both heavy industry and light industry are energy-intensive industries, and the growth of the national economy largely depends on the development of the industrial sector, so the carbon emission coefficient of the industrial sector is relatively higher than that of other sectors. Horizontally, the carbon emission coefficient of developing countries is often much lower than that of developed countries. The proportion of the energy industry in developing countries is too large and the energy consumption is high, so the carbon emission coefficient is high. These countries tend to encounter low-carbon barriers in their export trade, which is not conducive to the coordinated development of the overall economic system. In terms of industrial structure, the tertiary industry is the main industry in developed countries. Compared with industry, this industry produces less carbon emission and has more advanced technology and equipment, so it produces less carbon emission and a lower carbon emission coefficient.

Not surprisingly, the change of population in regions contributes little to the trade-related carbon emissions, whatever exports and imports (Fig. 4c and d). And even the flat trend line near zero occurs as well

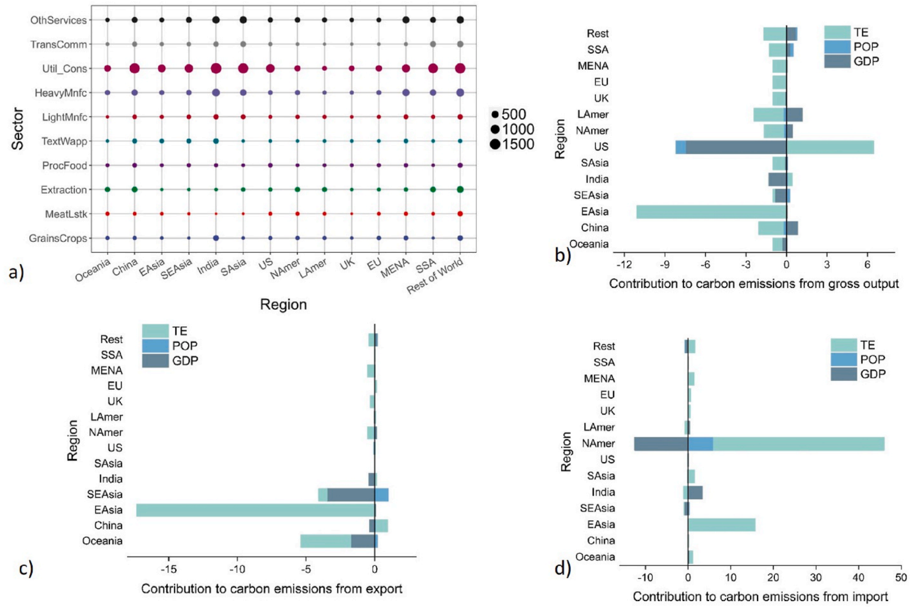


**Fig. 4.** Analysis of carbon emission intensity coefficient matrix (a) and index decomposition analysis of emissions embodied in trade of import and export and total output of each industry in each region (b–d).

in that of output (Fig. 4b), which suggests that demand is generally driven the supply and trade of the goods rather than simple population growth. It is noted that an exception for export footprints in MENA (Fig. 4c), the exploding increment in population plays a role where labor-intensive industries are dominant. However, GDP and technology factors have various impacts on carbon emissions, which is consistent with regional industry characteristics. In the wake of COVID-19, restrictions and lockdowns have disrupted supply chains to cripple the global industry. Quite business suspensions and closures causes production and trade-related carbon footprints are suppressed, where the overall fall in labor unemployment rate is one piece of evidence. Two attitudes towards the epidemic for the US and China mentioned earlier show completely opposite results of output carbon emissions contribution. In particular, the decline in GDP is directly responsible for the emission reduction in total output, while China maintains a slow rising economic situation and carbon footprints (Fig. 4b). It is interesting that the technology factor almost contradicts the GDP impact, mainly because enormous demand and advanced technology in economies are bound to have countervailing effects. For exports, especially big exporters of low consumer commodities like India and Oceania, the tight distribution channels and weak risk resistances imped trade transactions. On the contrary, the UK as developed country with conceptual or precision product exporters, has fewer restrictions on such production from home working so that the technical level becomes the first factor (Fig. 4c). Unfathomably, the contribution of technology factor to export carbon emission varies greatly (Fig. 4d), we speculate that is affiliated with the domestic market pattern, consumption habits and imports nature. Both the developing countries seeking technological transformation and the current technology-oriented developed countries show the obvious technology factor correlation. Meanwhile, the proliferation of dollar printing has made inflation and economic pressures more pressing, and then it is the trend of the times to seek cooperation through joint efforts.

## 4. Discussion

Carbon emissions from global supply chains has been overlooked for a long time. After the outbreak of COVID-19, the demand on energy has increased dramatically to maintain the basic living standard of human beings. As a result, evaluating carbon flows from global supply chain is vital for quantitative understanding of the impact of COVID-19. Drawing on GTAP analysis, we find that the pandemic has exposed the vulnerability of countries to global challenges at a time when the world still faces long-term systemic risks such as climate change. The outbreak of COVID-19 has led to a reduction in industrial activity in most countries, while having a mitigating effect on carbon emissions along the supply chain. As the pandemic fades and economic activities gradually resume, and the associated carbon emissions in the supply chain will rise again. To a certain extent, the choice of emission reduction measures in different countries is affected by different industrial structure. The long-term goal for countries that rely on industrial sectors to reduce carbon emissions remains to move away from carbon-intensive production and consumption. We propose the introduction of an emissions trading system to help reduce emissions under current mitigation measures. The public sector in some countries/regions, such as the U.S., has been responsible for increasing $CO_2$ emissions from domestic demand during the COVID-19 pandemic. Now it is necessary to intervene through the introduction of carbon emission reduction policies, such as carbon pricing and other measures, and in the future, it will even be necessary to further study carbon quotas and carbon offsets. In addition, we should pay more attention to the sustainable development of the supply chain, while achieving low-carbon development and addressing the opportunities and challenges under the climate change. For small enterprises in the supply chain, it is necessary to be self-sufficient as much as possible, advocate localized and regional production. This will not only prevent supply and demand imbalances caused by supply chain disruptions, but also reduce logistic carbon emissions. For countries that are heavily dependent on supply chains, more low-carbon production and supply centers should be sought to reduce carbon emissions from their own consumption. Fossil-fuel exporting regions, such as MENA, are upstream of the supply chain and are major energy suppliers. Faced with high emission reduction costs and low environmental benefits, they need to actively explore energy innovation and industrial structure transformation to achieve carbon reduction in emerging energy sources and provide a platform for its sustainable development. Large countries, such as China and India, need to avoid excess capacity of certain industrial sectors, achieving energy efficiency for carbon reduction. As big exporters, they also need to consider optimizing logistics and transportation in the supply chain, to ensure a higher level of supply and demand balance. However, in practice, members of the supply chain may not always cooperate with each other and may even compete. Therefore, the future research direction may be to use game theory to determine the equilibrium scheme of all members to cope with the changes in supply chain carbon emissions from the perspective of competition among supply chain members. In addition, the theme of carbon reduction equity should be emphasized in long-term emission reduction plans, as this will contribute to the achievement of sustainable development goals on a global scale.

## 5. Conclusions

We used GTAP to model the impact of COVID-19 in the short term and found that lockdown policies in response to the COVID-19 pandemic would lead to significant changes in $CO_2$ emissions. Through the input-output relationship within GTAP, we compared the changes in CO2 emission before and after the outbreak of the pandemic. We found that total $CO_2$ emissions in the 14 countries were 6.01% lower than in the absence of epidemics, and $CO_2$ emissions from the intermediate consumption and end-use products were reduced by 7.29% and 8.01% respectively. Despite the decline in global $CO_2$ emissions, the total emissions of China and the US still maintained an increasing trend, increasing by 1.71% and 0.81% respectively. The outbreak to the global supply chain of the huge impact, between each country/region is different because the proportion of its industrial structure, thus caused the influence degree of the relevant import and export department, and the area of import and export carbon before and after the outbreak of the percentage of its carbon output reflects the outbreak of policy adjustment/support barycenter offset making industries. In a word, the proportion of import and export carbon emissions decreased due to the epidemic. Except for the America (import and export), SSA, EU (import and export) and India (export), the share of export carbon emissions of other countries/regions did not decrease much, about 5%, and the share of import carbon emissions differed greatly. In 14 countries/regions, the carbon emission coefficient of industry and service industry is significantly higher than that of agriculture and other sectors, and the technological advantages of developed countries make their carbon emission coefficient smaller than that of developing countries. Through index analysis, we found that trade contributed little to carbon emissions in regions with population changes, while GDP and technological factors showed an opposite trend on carbon emissions. Our study shows the contribution of the outbreak to global emissions reductions, as well as the mitigation measures and strategies that can be adopted by different countries and regions after an orderly economic recovery.

## CRediT authorship contribution statement

**Yuru Liu:** Methodology, Data collection and . **Jingyu Zhu:** Methodology, Data collection and . **Christopher Padi Tuwor:** Writing – review & editing. **Lei Yu:** Writing – review & editing. **Ke Yin:** Conceptualization, Methodology, Writing manuscript, Writing supporting information, Writing – review & editing.

## Declaration of competing interest

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

## Data availability

Data will be made available on request.

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