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Cascading impacts of global metal mining on climate change and human health caused by COVID-19 pandemic

Yao Wang a, Heming Wang a, Peng Wang b, Xu Zhang a, Zhihe Zhang a, Qiumeng Zhong c, Fengmei Ma a, Qiang Yue a, Wei-Qiang Chen b, Tao Du a, Sai Liang c, "

a State Environmental Protection Key Laboratory of Eco-Industry, Northeastern University, Shenyang, 110819, People’s Republic of China
b Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen, 361021, People’s Republic of China
c Key Laboratory for City Cluster Environmental Safety and Green Development of the Ministry of Education, School of Ecology, Environment and Resources, Guangdong University of Technology, Guangzhou, 510006, People’s Republic of China

1. Introduction

The COVID-19 pandemic has posed unprecedented challenges to global supply chains and created exceptional socioeconomic hardships (Diffenbaugh et al., 2020; Guan et al., 2020). Among the global supply chains, the metal mining and production sectors are of particular concern because of their high economic value, environmental impacts, and relevance to low-carbon technologies (Wang et al., 2022; Hu et al., 2023). The use of certain metal minerals, such as lithium and cobalt, will need to ramp up by nearly 500% to 2050 in relation to 2018, while the global demand for metals used to deploy wind, solar, and geothermal power, as well as energy storage, will rise to 3 billion tonnes required to transition to a low-carbon economy (Hund et al., 2020). The consumption of critical metals has increased sharply, and as a result, demand and supply were stretched before the COVID-19 pandemic (Eggert, 2011; Hayes and McCullough, 2018). Moving forward, metal supply assurance will be increasingly important worldwide to ensure resource security, which is in line with the Sustainable Development Goals (SDGs) launched by the United Nations (Franks et al., 2022). As of July 2020, more than 275 metal operations had been disrupted, and the direct loss is estimated to be nearly 9 billion US dollars (at current prices) (S&P, 2020). Latin America and Africa have been the most significantly affected. For example, Peru’s lockdown disrupted 12% of the global copper output in 2020 (IEA, 2020), and Chile closed its borders in April 2021 as COVID-19 cases soared, worsening the tight global supply of copper (Writer, 2021). This significant disturbance to the mining sectors can have important cascading impacts on the global economy and environment through the globalized supply chains. Furthermore, finding low-carbon pathways to address the ecological crisis while promoting economic recovery is necessary to achieve the targets specified in the Paris Climate Agreement (IAP, 2020; Shan et al., 2020; Shao et al., 2022). Following the pandemic, global and science-based solutions and green recovery strategies on the supply side of the metal mining sector will also need to be devised and implemented. Thus, characterizing the cascading effects of this disruption on the economies, climate change, and human health of different countries through global supply chains is the prerequisite for solving the above problems.
For the influence on global metal mining caused by the COVID-19 pandemic, most recent studies have focused on the pandemic’s effect on metal prices and investments (Habib et al., 2021), the establishment of early warning mechanisms for emergencies (Zhu et al., 2021), and the mitigation of the negative effects of metal mining and production on low-carbon technologies (Akcil et al., 2020; Goldthau and Hughes, 2020). However, few studies have quantitatively analysed the effects of metal mining disturbances on the economic output of nations. The input-output (IO) model has been widely used for disaster impact analysis, which is a tool for measuring the effects of sudden external shocks on the economy (Koks and Thissen, 2016; Okuyama and Santos, 2014). The IO model is used to assess the economic impacts of any sectoral supply change through the linkage across countries embodied in the input-output table (Rocco et al., 2020; Shao et al., 2022). Some scholars have used this method to carry out related studies at the global (Lemen et al., 2020), national (CottaFava et al., 2022), and regional levels (Dyason et al., 2021). This method emphasizes interactions between producers and consumers and underlines their role in contributing to loss (Rose and Lim, 2002; Zeng and Guan, 2020).

Furthermore, mining and industries related to metal can be a detrimental and intense stressor on the environment and human health (Dialga and Ouoba, 2022; Zhao et al., 2019), whilst also including the mental and intense stressor on the environment and human health (Lenzen et al., 2020), national (Cottafava et al., 2022), and regional levels (Dyason et al., 2021). This method emphasizes interactions between producers and consumers and underlines their role in contributing to loss (Rose and Lim, 2002; Zeng and Guan, 2020).

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The global environmental extended multiregional input-output (EE-MRIO) model makes it possible to calculate the climate change and human health impacts caused by sudden changes. The EE-MRIO model is widely used to analyse trade-related environmental impacts, such as carbon emissions (Davis and Caldeira, 2010), material consumption (Wang et al., 2020b; Wiedmann et al., 2015), mercury emissions (Chen et al., 2019; Qi et al., 2019), and the use of scarce water resources (Huang et al., 2015; Qu et al., 2018; Wu et al., 2022). Applying the EE-MRIO model can capture supply-chain-driven impacts across regions for multiple environmental indicators and support measures for international cooperation between primary suppliers and emitters of direct emissions from the supply viewpoint (Li et al., 2022; Liang et al., 2017).

Here, we assess the cascading effect of the disruption of the global metal mining sector caused by the COVID-19 pandemic on the economy, emissions, and human health. First, we evaluate how the pandemic affected metal mining production based on the database of metal production at risk built by S&P Global Market Intelligence (S&P, 2020) and 2020 metal mining statistics (Table S1 in Supplementary information). We then use the EE-MRIO model, linking metal mining production data and EXIOBASE (version 3.6) data, to evaluate the economic losses (measured by production output) and the environmental and human health gains of nations compared with conditions without COVID-19 (see Methods). In addition to exploring the economic, environmental, and health impacts of nations associated with metal supply chains, our analysis makes it possible to quantify the relative contributions that the disruption of the mining of different metals made to the benefits that countries received. This quantification aids in designing green economic stimulus policies that will help achieve the long-term temperature targets of the Paris Agreement and improve human health following the COVID-19 pandemic.

2. Methods and data

2.1. Environmental and human health impacts

In this study, we selected six main categories of emissions (CO2, PM2.5, NMVOC, N2O, NH3, and CH4) to reflect the effects of climate change on various regions. The emission inventories that have not impacted the industry chain due to the pandemic were obtained from the environmental satellite table in the EXIOBASE database (Stadler et al., 2018). Human health damage impacts caused by pollutant emissions were computed by multiplying pollutant emissions with corresponding life cycle impact (LC-IMPACT) characterization factors (Li et al., 2020). The LC-IMPACT method is one of the Life Cycle Impact Assessment (LCIA) methods that offers characterization factors to quantify the endpoint environmental impacts, such as human health damage (the unit is disability-adjusted life years (DALY)) (Verones, Francesca et al., 2020). Four impact categories based on selected pollutant emissions include climate change, ozone depletion, photochemical ozone formation, and particulate matter (PM) formation, all of which affect human health (Verones, Francesca et al., 2020).

The quantity of each sector’s human health impacts $f_h$, is then calculated by Eq. (1):

$$ e_h = e_p \times CF $$

where the $m \times n$ matrix $e_h$ indicates $m$ categories of human health impacts by $n$ economic sectors. The $k \times n$ matrix $e_p$ represents the emissions of $k$ categories by $n$ economic sectors. The $m \times k$ matrix $CF$ stands for the LC-IMPACT characterization factors converting $k$ categories of emissions into $m$ categories of human health impacts in region $r$.

2.2. Global EE-MRIO model

We constructed the EE-MRIO model by using the EXIOBASE database, which included the monetary flows of 49 regions and 200 product groups with relatively high sectoral details and extensive environmental data (Stadler et al., 2018). Also, the database disaggregated “mining and quarrying” from “manufacturing of basic metals” activities, which enabled us to assess the effects of the extraction of each metal and improve the reliability of the results.

Given that lockdown measures have partly or wholly closed metal mines during the pandemic, we calculated income-based emissions and the human health damage of nations to evaluate the impacts on interregional trade on the supply side. The basic equation of the MRIO model is given by

$$ x = v(I - B)^{-1} = vG $$

where $x$ is the $1 \times n$ vector of the total input of region sectors (each sector total input equals its total output); $v$ is the $1 \times n$ vector of the value-added creation of each regional sector; and $B = (b_{ij})$ is the $n \times n$ matrix of the direct-output coefficient. Element $b_{ij}$ equals the direct input from sector $i$ in region $s$ to sector $j$ in region $t$ divided by the total output of region sector $i$. $G = (I - B)^{-1}$ is the $n \times n$ matrix, which is known as the Ghosh inverse matrix; the element $G_{ij}$ represents coefficients specifying the proportion of the total output of sector $i$ in region $s$ used by each primary input of sector $j$ in region $t$. Matrix $I$ is an identity matrix.

By defining a $1 \times n$ intensity vector $f$ to represent the $k$-th emissions $e_p$ or the $m$-th human health damage $e_h$ of each region sector for its unitary output, as shown by Eq. (3), we can calculate supply-side emissions or human health damage before the pandemic by Eq. (4):

$$ f = e(x)^{-1} $$

$$ E' = v'Gf' $$
where e represents the k-th direct emissions $\phi_k$ or the m-th human health damage $e_m$ of region sectors (indicated by $1 \times n$ row vector e); the column vector $x'$ represents total outputs of region sectors; $E'$ is income-based emissions or human health damage of each sector of region $r$, $f'$ denotes the transposition of vector $f$. The hat ‘$\ ^\prime$’ means diagonalizing the vector x. The notation ‘$\ ^\top$’ means the transposition.

During the COVID-19 outbreak, the metal mining sector has faced the risk of not having a sufficient supply of labour to meet production requirements. The negative impacts of local production can be traded directly or indirectly to the production of external regions through global supply chains (Qu et al., 2018). In this study, a pathway linking reductions in metal extraction to potential output losses for each sector throughout 2020 was conceived. The potential direct input loss ($U'_l$) from the reduction in metal production in the case of the pandemic is defined as:

$$U'_l = d'_l \times v'_l$$  \hspace{1cm} (5)

where $d'_l$ is the vector of the decreasing proportion of metal extraction in the metal mining sector l of region r. Considering that we focus on the economic, environmental, and human health impacts stemming from the reduction in metal mining sectors, we set the other sectors as 0 in the calculation.

All direct and indirect economic losses, decrease in emissions, and decrease in human health damage in region r stemming from the reduction in metal mining sectors can be expressed as:

$$\Delta x' = U'_l \times (I - B)^{-1} = U'_l \times G$$  \hspace{1cm} (6)

$$\Delta E' = U'_l Gf'^\top$$  \hspace{1cm} (7)

The elements of the vector $\Delta x'$ indicate the economic losses of each region enabled by the primary inputs of region r. The elements of the vector $\Delta E'$ represent the environmental or human health impact reduction enabled by the primary inputs of region r.

2.3. Data sources

In this study, eight categories of metals (including copper, lead, nickel, zinc, iron, cobalt, lithium, and molybdenum) were examined. Metal data were collected from S&P Global Market Intelligence (S&P, 2021) and the statistical yearbooks of various regions for 2020. For regions without published metal mining statistics, we used the database of metal production at risk built by S&P Global Market Intelligence (S&P, 2020) to obtain data on the reduction in the entire year’s metal mining production. Because this was issued on June 25, 2020, it permitted only the decrease in global metal mining for the first and second quarters to be determined. We collected metal mining data for the third and fourth quarters based on previously published data and report them as a supplement (Table S1). Given that the pandemic began to break out globally in the second quarter, we supplemented missing data by assuming that the stringency of the lockdown measures in the third and fourth quarters was the same as those in the second quarter. For comparison, we use S&P Global Market Intelligence’s metal production forecast for 2020 in the pre-pandemic period to estimate the pandemic-induced decline in metal production (S&P, 2021). This study uses the MRIO table in 2015 derived from the EXIOBASE (version 3.6) database (Stadler et al., 2020). The EXIOBASE database provides detailed data for the 49 regions (Table S2) and 200 product classifications (Table S3), for which environmental satellites contain data on industry-specific and final demand air emissions for pollutants. Since the EXIOBASE database’s currency unit is the euro, all currencies were converted to 2015 US dollars using the average exchange rate for easy reference (UK, 2021). The life expectancy at birth data was derived from the world bank database (World Bank, 2022).

3. Results

3.1. Effects of the metal mining disruption on the economy during the COVID-19 pandemic

Fig. 1 shows the economic impacts associated with the reductions in metal mining in 2020 caused by COVID-19. Overall, the total global economic losses reached 116.9 billion US dollars, compared with conditions without COVID-19. The economic output losses were concentrated on the American continent (Fig. 1a), as this is the central area of metal ore production and has been affected the most by lockdown measures (Magadula, 2020). In terms of metal categories, the reduction in copper mining had the greatest effect on the global economy (59.9 billion dollars), followed by iron (27.9 billion dollars) and nickel (13.1 billion dollars) (Table S4). In addition, refined metal production in multiple countries was affected by temporary smelter shutdowns, which affected the entire industrial chain. Thus, the COVID-19 pandemic has also significantly affected the metal refining industry and metal manufacturing, leading to economic losses in various regions, especially the United States, Mexico, and East Asia (China, South Korea, and Japan).

Among countries situated upstream in the industrial metal chains, such as China, rest-of-the-world America (RoW America), and Canada, economic output losses of 32.1, 15.5, and 12.8 billion US dollars were observed, respectively (Fig. 1b). Among those, the impact of copper mining mainly on China and RoW America ranked the highest (20.3 and 11.2 billion US dollars, respectively), whereas the reduction in iron ore mining had the most considerable effect on Brazil’s economy (11.9 billion US dollars). RoW America (including Peru and Chile) and Brazil are major mining resource suppliers worldwide, and thus their resource supply disruptions have driven large amounts of upstream economic losses. Significant economic losses were also observed for countries located downstream in the industrial metal chain. The economies of the United States, Germany, and East Asia, whose primary industries are metal processing, machinery manufacturing, and automobile manufacturing, were affected the most. Specifically, in the United States and Germany, the economic losses induced by the reduction in metal mining were as high as 7.2 and 1.4 billion US dollars, respectively. For Japan, South Korea, and Chinese Taiwan, with few domestic resources, these losses were 4.5, 3.9, and 2.8 billion US dollars, respectively. In order to mitigate this influence, countries have been working to maintain metal production to prevent further losses. For example, iron ore production in China was 7% higher in the second quarter of 2020 than over the same period in 2019 (NBS, 2021). Additionally, mining giant Vale announced to resume production at Brazil’s Itabira mining complex on June 17, 2020 (Bnamericas, 2020). However, the COVID-19 lockdown still had a non-negligible impact on some countries. For example, in Peru, copper production through July 2020 fell by nearly 23% from that in the same period in 2019 (USGS, 2021).

3.2. Effects of the reduction in metal mining on emissions during the COVID-19 pandemic

The reduction in emissions across countries and regions stemming from the reduction in metal mining in 2020 is shown in Fig. 2. Global CO2 emissions decreased by 32.6 million tonnes because of the disruption of the metal mining sector, equivalent to more than the annual CO2 emissions of Hungary (33.6 million tonnes), Sweden (33.1 million tonnes), and Switzerland (26.9 million tonnes) (Fig. 2a). In addition, some regions experienced significant reduction in CO2 emissions (Fig. 2b). China experienced the largest reduction in CO2 emissions (12.2 million tonnes), followed by Canada (5.3 million tonnes) and RoW America (4.1 million tonnes). The impact of primary metal inputs dominated the income-based CO2 emission reduction of China’s metal industry chain, the largest CO2 emitter in the world. In practical terms, the impacts of the primary inputs of copper, iron, and nickel caused CO2
emissions reduction of 5.6, 4.7, and 0.9 million tonnes, respectively, in China. The metal production-related industries with significant emissions reduction in other regions include iron in Brazil (3.0 million tonnes) and RoW America (1.6 million tonnes), and copper in RoW America (1.9 million tonnes) and Canada (1.6 million tonnes). The abovementioned regions are the primary producers of metal mines. The impacts of mine production and related downstream industries (such as smelters and refineries) owing to restrictions implemented by countries in response to the COVID-19 pandemic promoted reductions in CO₂ emissions.

In addition to CO₂ emissions, our results demonstrate reductions in the emissions of PM₂.₅, NMVOC, CH₄, NH₃, and N₂O stemming from the reduced production of primary metal minerals. As a large amount of smoke and dust can be generated during the mining and smelting of metals, lockdown policies induced global decreases in PM₂.₅, NMVOC, CH₄, NH₃, and N₂O emissions of 59.8, 37.3, 36.8, 5.2, and 0.4 thousand tonnes, respectively (Fig. 2c-l and Table S5). Notably, the reduction with the largest emission ratio changes was PM₂.₅ (Table S5). The two regions that experienced the greatest decrease in PM₂.₅ emissions because of metal mining were RoW America (22.7 thousand tonnes) and Brazil (16.7 thousand tonnes), which are also the leading metal suppliers in the world. In 2020, the countries with the largest decrease in other pollutants were China for NMVOC, CH₄, and N₂O (10.4, 19.1, and 0.2 thousand tonnes, respectively) and RoW America for NH₃ (4.2 thousand tonnes). It was found that China was the country that experienced the most significant reduction in emissions, which was attributed to the fact that the effect on copper mining and related industries made the most outstanding contribution to the reduction in CH₄ (8.9 thousand tonnes) and NMVOC (6.4 thousand tonnes) emissions. In addition, CH₄ emissions from copper mining and the industrial chain overall during the COVID-19 pandemic made the most considerable contribution to the reduction in emissions in other countries (Table S6). It is not surprising because copper mining and related industrial processes have been considered significant sources of greenhouse gas (GHG) emissions (Alvarado et al., 2002; Northey et al., 2013). Elsewhere, copper minerals, iron ores, and lead-zinc minerals were responsible for reducing PM₂.₅ emissions in RoW America by 19.6, 1.4, and 0.9 thousand tonnes, respectively (Fig. 2d). RoW Asia and Pacific ranked first in reducing NH₃ emissions, and the reduction in copper mining was responsible for a reduction in NMVOC emissions of 1.4 thousand tonnes.

3.3. Benefits to human health associated with the reduction in emissions

The long-term effects of worsening air quality are associated with an increased risk of chronic obstructive pulmonary diseases, lung cancer, and stroke (Cohen et al., 2017). Thus, in this regard, the reduction in emissions accompanying the pandemic has decreased healthy years lost due to premature death or disability. Although more than 20.5 million years of life have been estimated to be lost to COVID-19 worldwide in 2020 (Pifarre i Arolas et al., 2021), the reduction in metal mining indirectly provided some health benefits. In this study, we defined life extension as the benefiting population equivalent, which was derived from the reduction in disability-adjusted life years divided by the human life expectancy indicator in various regions to characterize the extent of the human health benefits. The world experienced an increase of 1,024 benefiting population equivalents, or approximately 78,000 DALY were reduced because of the reduction in metal mining (Table S7 and Table S8). Iron and copper made the largest contributions to the reduction in DALY (38.6% and 38.4%, respectively).

The reduction in emissions will lead to less climate change and stratospheric ozone depletion, all of which positively affect public health worldwide. Fig. 3 shows the top twenty regions worldwide that experienced the greatest benefits to human health stemming from emission decreases. The most substantial health benefits were concentrated in regions where more metal ores were extracted, such as Canada, Brazil, and RoW America. The health benefit ratios of these top three regions among the global population were as high as 1.1%, 0.6%, and 0.5%, respectively, compared with the damage before the COVID-19 pandemic in these regions. China had the largest decline in health impacts (17,892 DALY, 233 benefiting population equivalents), and the copper industry had the most significant impact (8,222 DALY, 107 benefiting population equivalents) worldwide (Table S9 and Table S10). Canada (7,513 DALY, 92 benefiting population equivalents) and RoW America (5,898 DALY, 78 benefiting population equivalents) ranked second and third in terms of reducing damage to human health among the total global population (Table S9 and Table S10).

In addition, the impact of photochemical ozone formation and particulate matter formation on human health damage is changed in the DALY of local inhabitants as emissions have decreased in the source region. The human health ratio for all inhabitants in RoW America ranked first (2.3%) (Fig. 3). The rates of benefitting human health in Brazil and RoW Africa were 2.0% and 0.3%, respectively. Notably, China, RoW Asia and Pacific, and RoW America were the three regions where there was the greatest impact on local human health; the reduction in human health damage among these top three regions was as high as 18,075 DALY (236 benefiting population equivalents), 2,846 DALY (38 benefiting population equivalents), and 2,824 DALY (37 benefiting population equivalents), respectively (Table S12 and Table S13). As China has the largest population, serves as the world’s factory for metal industrial manufacturers, and generates a large amount of emissions, it experienced substantial health benefits because of emissions reduction.
Fig. 2. The reduction in emissions stemming from the effect on metal mining during the COVID-19 pandemic. Notes: The six pollutants are in six groups. a, c, e, g, i, and k show the reduction in emissions in different regions for CO, PM, NMVOC, CH, NH, and N, respectively. b, d, f, h, j, and l show the top 10 regions experiencing the most significant emissions reduction stemming from the reduction in metal mining. RoW Africa indicates rest-of-the-world Africa. The emissions reduction is provided in Table S5 and Table S6.
Fig. 3. The top twenty regions experienced the most significant health benefits from emissions reduction. Note: The x-axis shows the proportion of the reduction in human health damage compared to before the COVID-19 pandemic in this region. The left part shows the worldwide health benefits from regions that reduced the impacts of climate change and stratospheric ozone depletion. The right part shows the local health benefits from regions that reduced photochemical ozone formation and particulate matter formation. The top twenty regions in the chart are ranked according to the DALY data. The proportions of DALY reduction in different regions are shown in Table S11 and Table S14.

Fig. 4. Composition of the global economic output losses, emissions reduction, and human health benefits associated with the COVID-19-mediated reduction in metal mining among selected countries and regions. Notes: a Comparison of global economic losses and emissions reduction. b Comparison of global economic losses and human health benefits. The black dashed lines in the figures represent the division of economic losses, environmental income, and human health benefits. The area above the black dashed line corresponds to more significant economic losses but lower emissions reduction (Fig. 4a) or human health benefits (Fig. 4b) stemming from the reduction in metal mining associated with the pandemic. The red frames indicate the countries and metal mining sectors that should prioritize restoring production capacity.
4. Discussion

Green economic stimulus policies for economic recovery are crucial for preventing global warming (Evans and Gabbatiss, 2020; Forster et al., 2020). The new insights from the cascading effects of the disruptions of metal mining associated with the pandemic on the economy, climate change, and human health can provide implications for developing green economic stimulus policies following the COVID-19 pandemic.

From a global perspective, metal mining sectors with greater economic losses and a lower reduction in environmental impacts and human health damage in specific regions should be given high priority when designing green economic recovery policies through global supply chains (Fig. 4 and Fig. S1-4). For example, the copper mining sector of RoW America (including Peru and Chile) in the red frame experienced more significant economic losses and lower benefits for environmental and human health; the same was the case for the copper and lead-zinc mining sectors of Mexico and the copper mining sectors of China and the United States. In contrast, the iron mining sectors in countries received relatively more minor economic losses but more environmental and health benefits, indicating they should not be given priority when developing green economic stimulus policies. In 2021, the global economic recovery and rising investment in low-emission technologies boosted metal mining production (USGS, 2021). However, few measures for the environmental impact dimension have been identified in metal mining recovery plans (OECD, 2022). Well-designed green recovery plans can generate the double dividend of increased resource security and environmental outcomes. Thus, metal’s economic importance and environmental risk should be simultaneously considered in allocating international assistance and emergency aid based on the type of mining sector to optimize the achievement of a green economic recovery.

From the perspective of international cooperation, countries and
regions are linked through metal production chains to a substantial degree. Specifically, we showed how international trade transmits metal mining risks to the global economy and affects the environment and human health (Fig. 5). Countries or regions relying on imports took major economic hits during the COVID-19 pandemic. For example, Bulgaria, India, Japan, and China suffered the most considerable economic output losses from RoW America by 0.13%, 0.04%, 0.04%, and 0.04%, respectively. On the other hand, in terms of CO₂ emissions reduction, Bulgaria and China benefited from RoW America by 0.05% and 0.04%, respectively. These findings highlight the importance of global cooperation in designing economic stimulus policies.

To effectively boost economic growth, resource-importing countries, such as South Korea, Japan, and Finland, need to strengthen their national cooperation with resource-exporting countries by providing medical supplies to aid pandemic control. Moreover, this study’s major international pairs identified from the supply side provide a valuable reference for seeking international partners to control global CO₂ emissions and benefit human health (Fig. 5 and Fig. S5). For example, resource-exporting nations (e.g., Canada) could transfer capital and their available technologies to aid the development of end-of-pipe emission reduction technologies in metal industries and to benefit human health in resource-importing countries and regions (e.g., Bulgaria, China, Chinese Taiwan, and Turkey) (Qi et al., 2019). From another perspective, for exporters, metal mining activities can lead to CO₂ emissions and threaten biodiversity (Gan and Griffin, 2018; Sonter et al., 2020). Therefore, several developed importing countries (e.g., Japan and Sweden) can consider formulating investment policies to assist with reducing the CO₂ emissions and ecological damage caused by the metal mining of resource exporters, such as Peru, Mexico, and Brazil. When these other determinants of comparative advantage are in place, a resource-abundant country tends to export resources to countries with a relative abundance in capital and skilled labour and import capital-intensive goods in return (WTO, 2010). Moreover, the design of a flexible and dynamic border tax adjustment mechanism can generate a double dividend for both resource-exporting and resource-importing nations based on the cascading effects of economic and environmental impacts along global supply chains (Fischer, 2011; Jakob and Marschinski, 2013).

In the long term, for countries, promoting resource-efficient production and reducing dependency on raw metal ores is the key to reducing the risks associated with international metal production chains (Luna-Nemecio et al., 2020; Wang et al., 2020a; Watari et al., 2020). Aside from diversifying metal mining areas, nations should consider pluralistic sources of metal resources when devising national strategies for utilizing such resources. Metal trade diversification can be promoted by identifying key trading partners and a wide range of investment policies targeting metal mineral-rich countries with low environmental impacts on the world. In most cases, metal recycling can provide significant economic and environmental benefits (Kirchherr et al., 2017; Nuss et al., 2019; Wang, H. et al., 2022). Thus, long-term strategies should include redesigning technologies to use diversified or alternative materials and strengthening the recycling efficiency of secondary resources.

Several potential limitations should be considered in this study. To further improve the estimation, the model presented in this study is required to incorporate the mine tailings of the mining of metals into further analysis. In addition, the global economic recovery associated with intensive fiscal stimulus measures may cause the negative environmental impact of uncertain policies. Future studies investigating how different fiscal stimulus packages of metal mining exert heterogeneous impacts on economic output and the environment through global supply chains are warranted by combining the computable general equilibrium (CGE) and IO models.

5. Conclusions

The COVID-19 pandemic has been an unprecedented threat to metal mining through isolated outbreaks and government mandated shutdowns. This study applied EEIO and LC-IMPACT methods to assess the effects of metal mining disturbances on climate change and human health at the global level in 2020. The results show that the COVID-19 pandemic reduced global metal mining by 10-20%. Overall, this reduction subsequently led to losses in global economic output of approximately 117 billion US dollars, reduced CO₂ emissions by approximately 33 million tonnes (exceeding the annual emissions of Hungary), and reduced human health damage by 78,192 DALY. Notably, major disruptions such as copper and iron mining mainly occurred in RoW America and Brazil, which had a big impact on other countries. China and RoW America were the most affected by both the overall impact of environmental and human benefits. Thus, sectors with greater economic losses and a lower reduction in environmental and human health damage in specific regions should be given high priority when designing green economic recovery policies from a global perspective, such as the copper mining sector of RoW America. Long-term strategies should include redesigning technologies to use diversified or alternative materials and strengthening the recycling efficiency of secondary resources. On the basis of the cascading effects of mining disruption on the economy, climate change, and human health, this study can provide improved guidance for government policy on designing green economic stimulus policies toward more sustainable metal mining in countries all over the world.

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.

Acknowledgements

This study was financially supported by the National Natural Science Foundation of China (72293602, 52070034 and 41871204).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106800.

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