communications
earth & environment

ARTICLE

https://doi.org/10.1038/s43247-023-00914-2 OPEN

Responses to the COVID-19 pandemic have impeded progress towards the Sustainable Development Goals

Cai Li[1,2,6], Zhongci Deng[1,6], Zhen Wang[1,3✉], Yuanchao Hu[4], Ling Wang[1], Shuxia Yu[1], Wei Li[1], Zhihua Shi[1,5✉] & Brett A. Bryan[2]

COVID-19 pandemic responses have brought unprecedented challenges to the United Nations 2030 Agenda for the Sustainable Development Goals (SDGs) and a quantitative, multi-dimensional assessment of the impacts of these responses on SDG progress is required. Here, we use an adaptive multi-regional input–output model to quantitatively assess the impact of pandemic responses on global and national SDG progress and show that COVID-19 pandemic responses reduced overall progress towards the SDGs by 8.2%, with socio-economic sustainability declining by 18.1% while environmental sustainability improved by 5.1% compared with the business-as-usual trend. Developing countries suffered greater reductions in overall sustainability (9.7%) than developed countries (7.1%). Under all post-pandemic futures, pandemic responses were found to impede overall progress towards the SDGs and worsened inequality between countries, particularly for socio-economic targets. A post-pandemic strategy toward the SDGs requires sustainable pandemic responses which not only address inequality among countries but also lessen the trade-offs between SDGs.

[1] College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, China. [2] School of Life and Environmental Sciences, Deakin University, Melbourne VIC, Australia. [3] Interdisciplinary Research Center for Territorial Spatial Governance and Green Development, Huazhong Agricultural University, Wuhan 430070, China. [4] School of Resources and Environmental Sciences, Wuhan University, Wuhan 430079, China. [5] CAS Center for Excellence in Quaternary Science and Global Change, Xi'an 710061, PR China. [6] These authors contributed equally: Cai Li, Zhongci Deng. ✉email: sinoo@mail.hzau.edu.cn; pengshi@mail.hzau.edu.cn

The United Nations has declared the 2020s the "Decade of Action" towards the Sustainable Development Goals (SDGs), requiring the 193 committed nations to achieve 17 goals and 169 targets spanning the environment, the economy, and society[1,2]. Since 2020 however, the COVID-19 pandemic has challenged this grand ambition[3,4]. Previous studies indicate that nearly two-thirds of the SDG targets may be under threat from the impact of COVID-19 pandemic responses, and some responses may even be counterproductive to the sustainability agenda[5]. For instance, movement restrictions implemented to control virus transmission have reduced environmental degradation, but also caused substantial social isolation and economic loss[6–8]. Similarly, fiscal stimuli implemented to accelerate economic recovery may also increase greenhouse gas emissions and exacerbate climate change[9]. A comprehensive, integrated, and quantitative assessment of the impact of COVID-19 pandemic responses on social, economic, and environmental aspects of sustainability, particularly in countries already burdened by poverty and conflict, is now urgent[9]. Failing to do so may mean that several SDGs will not be met by 2030[5].

Previous research has assessed the influence on SDG progress of COVID-19 and the public health and economic responses to it[10–13]. Some studies have evaluated the impact of individual pandemic responses on sustainable development. For instance, Falkendal et al. found that trade restrictions threatened the food security of developing countries[14]. Lenzen et al. found that the pandemic and associated movement restrictions reduced global consumption, income, and employment but also reduced greenhouse gas emissions and air pollution[8]. A few studies have also quantified the impact of multiple pandemic responses on individual aspects of sustainability, such as greenhouse gas emissions and employment[9,15]. However, different pandemic responses involve nuanced and heterogeneous impacts across different SDG targets, countries, and income groups, and these impacts may interact, leading to synergies and trade-offs between targets and exacerbating inequality between countries[11,16,17]. No studies have quantified the heterogeneous impacts of multiple COVID-19 pandemic responses on multiple SDGs. This issue is particularly important for informing future pandemic responses which will face a similar policy dilemma[5,18,19]. The absence of a quantitative and detailed understanding of the impacts of individual public health and economic measures generates a policy blind spot that must be addressed to coordinate global sustainable development with pandemic responses.

We developed a global adaptive multi-regional input–output (AMRIO) model to quantitatively assess the impacts of COVID-19 pandemic responses on global and national SDG scores, as represented by selected SDG targets and indicators. This model has been widely used to assess the economic consequence of disasters, e.g., pandemics, floods, and earthquakes, as it is able to identify the cascading effects between multiple sectors in a disequilibrium market induced by short- or medium-term shocks[6,9,15,20]. Other economic models such as input–output model and computable general equilibrium model are well-known for disaster impact assessment and able to explicitly reflect the interactions between supply and demand at the sectoral level, but they either lack the adaptive behavior of economic agents to capture the dynamic change in a disaster (e.g., input–output model) or overestimate the flexibility of the post-disaster market that is unlikely to reach equilibrium through price adjustment in the short term (e.g., computable general equilibrium model)[6,9]. However, the AMRIO model can simulate pandemic responses by reshaping labor, capital, and transportation constraints, thus enabling the quantification of economic, social, and environmental consequences by simulating direct and indirect results through supply chains. In this model, we consider the three most widely used response measures (i.e., movement restrictions, fiscal stimuli, and trade restrictions) and select eight SDG targets (four socio-economic and four environmental targets, Table 1) each of which have measurable indicators and available data (see "Methods").

In this study, we simulate the impacts of multiple pandemic responses on multiple aspects of sustainability during the United Nations Decade of Action. Based on the expectation of the end of COVID-19 and the utility of related response measures, we set 2023 as a break point[21]. First, we analyzed the impacts of pandemic responses on the SDG targets above during the COVID-19 pandemic period (from 2020 to 2023) by assessing national and global SDG progress under COVID-19 and a business as usual (BAU) scenario (a hypothetical no-pandemic scenario), measured in terms of SDG target scores. We then identified the impacts of movement restrictions, fiscal stimuli, and trade restrictions on SDG progress in 2020, when pandemic responses led to the most serious shocks to the global supply chain. Finally, we simulated SDG progress during the post-pandemic period (from 2024 to 2030) and discussed the inequality between nations under different policy options.

Results

Global sustainability under COVID-19 pandemic responses. We found that global SDG progress has been significantly hindered by COVID-19 pandemic responses, showing a V-shaped trend during the pandemic period (Fig. 1a). With the outbreak of COVID-19 in 2020, the global SDG score fell by 8.2%, from 55.7 to 51.1. A gradual recovery in the sustainability score then occurred from 2021 to 2023 with the demise of the pandemic, at a rate of nearly 2.8% per year, approaching the pre-pandemic level of 55.5 in 2023. The rapid short-term decrease in the global SDG score resulting from pandemic responses was followed by a recovery following the gradual phasing-out of pandemic responses. National SDG scores indicated significant inequality between countries. Under the COVID-19 pandemic, European countries, mainly developed countries, had the highest SDG scores, around 58.9. In contrast, Asian and African countries, mainly developing countries, had lower SDG scores, around 47.5 (Fig. 1b). These global and regional trends on SDG scores are consistent with the results from the United Nations[3,4].

COVID-19 pandemic responses further exacerbated inequality in sustainable development between different income groups. Compared with the BAU scenario (Fig. 1c, d), the sustainability of developing countries, including upper-middle-income countries, lower-middle-income countries, and low-income countries, was more seriously impacted by pandemic responses. The SDG scores of these three income groups were reduced by 9.6%, 10.5%, and 6.8% on average, respectively, by COVID-19 responses compared with the BAU scenario. Deterioration in developing country progress towards socio-economic targets was most pronounced, especially for SDG2.1, SDG8.1, and SDG9.2, which declined by 49.9%, 9.4%, and 20.5%, respectively. In particular, developing countries faced exacerbated undernutrition as a result of COVID-19 pandemic responses[14]. In comparison, the SDG progress of developed countries was more resilient to COVID-19 responses. Their SDG score decreased by only 7.1% on average, significantly outperforming that of developing countries (9.7% decrease). The worse-off sustainability scores of developing countries mainly derive from their increased vulnerability against SDG2.1 and SDG8.4. This phenomenon can be explained by the cascading effects of response measures in the global supply chain. With a high reliance on labor-intensive agricultural production, developing countries suffered a greater reduction in agricultural output (24.0%) than developed countries (20.2%) as movement

Table 1 Implications and representative indicators of selected SDG targets.

Type	SDG targets	Implication	Indicators	Indicator score
Socio-economic	2.1	End hunger and ensure access by all people	Prevalence of undernourishment (*PoU*,%)[a]	$S_{2.1} = f(PoU)$
	8.1	Sustain per capita economic growth	Economic growth (million of US dollars): real GDP per capita (*RGDP*)	$S_{8.1} = f(RGDP)$
	9.2	Promote inclusive and sustainable industrialization	Share of manufacture (%): manufacturing value added value added as a proportion of GDP	$S_{9.2} = f(MGDP/GDP)$ *MGDP* is GDP of manufacturing sector
	17.11	Significantly increase the exports of developing countries	Countries' share of exports (%)	$S_{17.11} = f(EXP_d/EXP_g)$ EXP_d and EXP_g is value of national and global exports, respectively
Environmental	6.4	Substantially increase water-use efficiency	Water stress index (%): freshwater withdrawal (*WW*) as a proportion of available freshwater resources (*WR*)[a]	$S_{6.4} = f(WW/WR)$
	7.2	Increase substantially the share of renewable energy in the global energy mix	Energy structure (%): renewable energy share in the total final energy consumption (*SRE*)	$S_{7.2} = f(SRE)$
	8.4	Improve progressively global resource efficiency in consumption and production	Material consumption (tonnes): domestic material consumption per capita[a]	$S_{8.4} = f(MC/POP)$ *MC* is material consumption; POP is national population
	13.2	Integrate climate change measures into national policies, strategies, and planning	Total greenhouse gas emissions per year[a] (CO_2 equivalent, million tonnes)	$S_{13.2} = f(GHG)$ *GHG* is total greenhouse gas emissions

[a]Indicates negative indicator which shows more sustainable performance when the indicator is smaller, while the rest is positive indicator. The function *f(x)* is used to indicate the standardization algorithm. We standardized each indicator ranging from 0 to 100. So that both positive and negative indicators show better performance when the indicator score approaches 100.

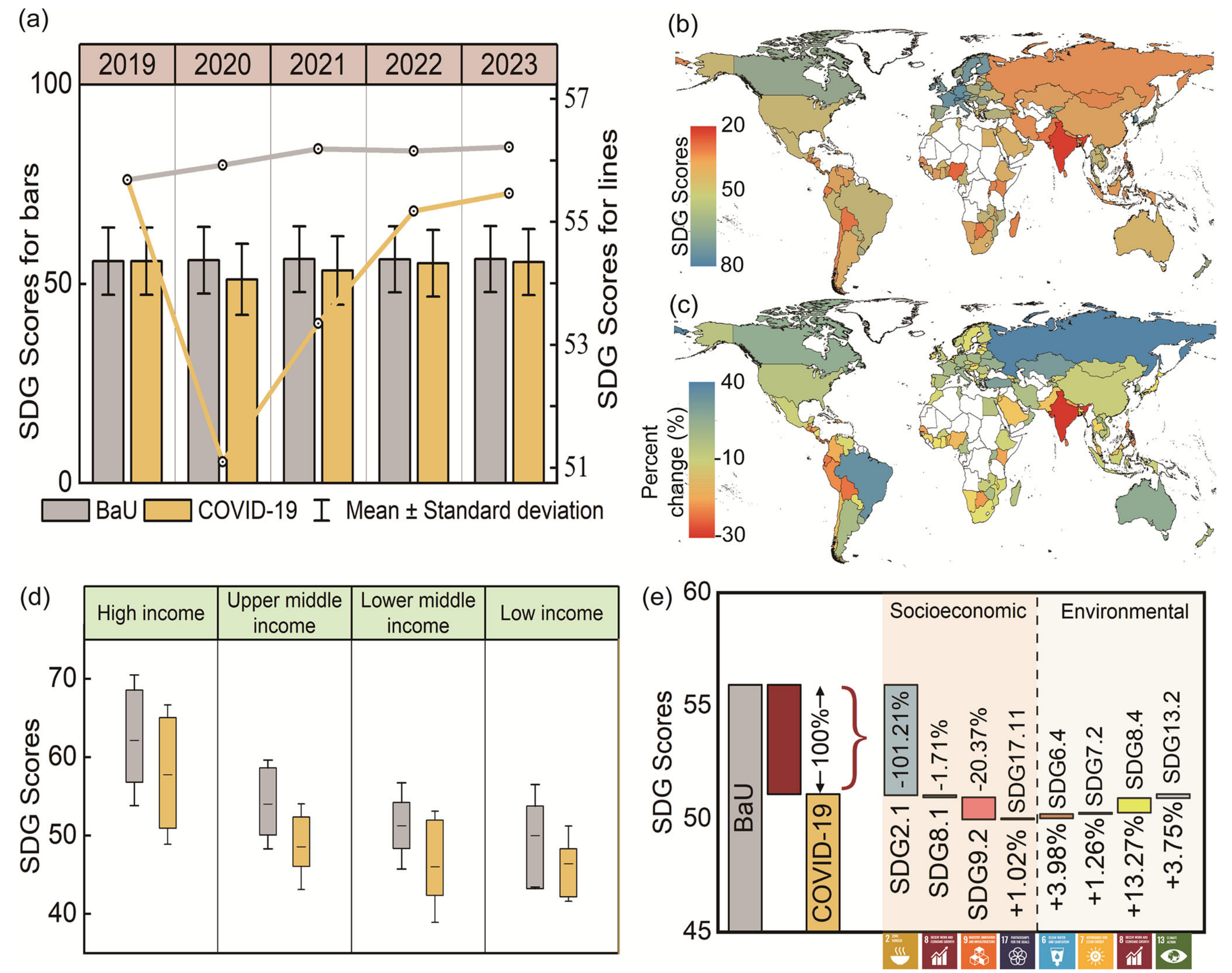

Fig. 1 The temporal and spatial changes in global SDGs. a Temporal change in SDG scores at the global level. **b** SDG scores for all countries under COVID-19 pandemic responses in 2020; the regions in white color indicate no data. **c** The impacts of pandemic responses on national SDG score changes between the COVID-19 pandemic and BAU scenario (shown as a percentage change). **d** The impacts of pandemic responses on different income groups in 2020; dark and light colors indicate SDG scores in the BAU scenario and the COVID-19 pandemic, respectively. **e** The impacts of pandemic responses on different SDG targets in 2020. In (**d**), the upper side of the box indicates the upper quartile, the lower side indicates the lower quartile, the black horizontal line represents the mean, the error bar represents the standard deviation. Credit (icons): the United Nations (SDG).

restrictions lead to a labor shortage and reduced the score of developing countries for SDG2.1 by 49.9%, compared to 36.2% in developed countries. Similarly, where pandemic response measures hindered industrial activities, developing countries reduced material consumption (25.5%) more steeply than developed countries (15.9%), causing a more pronounced increase in SDG 8.4 score in developing countries (10.7%) than in developed countries (4.4%).

In addition, the impacts of pandemic responses on socio-economic and environmental targets differed. Compared with the BAU, the four selected environmental targets all showed an improvement ranging from 2.8% for SDG7.2 to 7.4% for SDG8.4, an average increase of 5.1%. In contrast, selected socio-economic targets decreased by 18.1% on average, made up of a decline in SDG8.1, SDG9.2, and SDG2.1 by 4.1%, 23.8%, 48.4%, respectively, while SDG17.11 was unchanged. SDG2.1 was the most seriously threatened target, accounting for a 101.2% reduction in the global SDG score (see Fig. 1e). The reason is that import-dependent countries suffered from severe food shortages due to the disruption of the food supply chain. For example, the top 10 countries suffering most from decline in SDG2.1 are all import-dependent countries, where cereal import dependence ratios exceeded 50% from 2016 to 2018. In addition, other socio-economic targets such as SDG8.1 and SDG9.2 were also pressured by pandemic responses, seeing 1.7% and 20.4% reductions in SDG scores, respectively, largely as a result of movement restrictions. Countries that imposed harsher restrictions on movement, such as China and Peru, faced more significant disruptions to SDG8.1 and SDG 9.2, the scores for which decreased by more than 17.9%. Economic recession from 2019 to 2020 verifies these results. However, a slight rise (3.8%) in the socio-economic indicator SDG17.11 demonstrates that national export shares were mostly unchanged. This trend can be verified by the assessment of SDG indicators database from the United Nations[22], and suggests that international trade structure was not reshaped by pandemic responses, despite the value of national and global exports declining.

In comparison, all environmental targets experienced recovery during the pandemic period. SDG8.4 showed the largest improvement, with its global score rising by 7.4% compared with the BAU scenario. SDG8.4 was followed by SDG13.2, SDG6.4, and SDG7.2, which rose by 7.1%, 3.1%, and 2.8%, respectively, in 2020. Environmental recovery benefitted from reduced industrial production and transportation as a result of border closures, lockdowns, and social distancing[7,8]. Much higher positive environmental impacts occurred in countries that rely more heavily on highly polluting and resource-intensive industries, such as Indonesia, increasing 12.2% on average across four environmental targets. Existing data and research have supported the reduction in greenhouse gas reduction and energy consumption in Indonesia since COVID-19[23,24]. This is likely due to the strict and prolonged lockdowns which resulted in a greater reduction in industrial activities and a more substantial environmental recovery.

Different impacts of the three pandemic responses. We identified the different impacts of each pandemic response by comparing the results between individual pandemic responses and the BAU scenario in 2020. Our results suggested that movement restrictions played the most important role in hindering progress towards socio-economic targets by 30.5% (Fig. 2), especially SDG2.1 (45.8%), SDG9.2 (16.0%), SDG 17.11 (13.4%), and SDG8.1 (7.3%). However, movement restrictions also triggered an improvement in progress towards environmental targets of 3.1%, as there was a synergistic rise in the scores for SDG8.4 (6.0%), SDG7.2 (3.2%), SDG13.2 (1.8%), and SDG6.4 (1.8%). Furthermore, the stronger the movement restrictions were, the worse the decline in the socio-economic target scores (see Fig. 2) and, in turn, the better the performance against environmental targets. In summary, movement restrictions generated a beneficial outcome across the four environmental indicators but this came with a trade-off for socio-economic indicators mainly by stagnating industrial activities[6–8].

Fiscal stimuli had an opposite but weaker effect on SDG targets compared to movement restrictions (Fig. 2), confirming the synergies and trade-offs between SDGs in terms of the impact of pandemic responses. SDG2.1, SDG8.1, and SDG9.2 increased by 3.0%, 6.7%, and 0.1%, respectively, due to financial support for food supply, industrial production, and household consumption. However, fiscal stimuli also triggered additional environmental pressure, with SDG6.4, SDG7.2, SDG8.4, and SDG13.2 consistently decreasing by nearly 0.2%. Notably, fiscal stimuli significantly accelerated all socio-economic targets except SDG17.11 because most countries provided financial support biased towards domestic final demand rather than export markets. As a result, their export share was similar to the BAU. In general though, the positive effects of fiscal stimuli did not fully offset the negative impacts of movement restrictions.

Among the three kinds of response measures, trade restrictions had the lowest impact on SDG progress. Because most trade-related response measures to COVID-19 were temporary, lasting only a few months, and were small in scale, primarily addressing the agricultural sector. The percentage of countries with trade restrictions was also the lowest (12%), far less than the percentage of countries with movement restrictions and fiscal stimuli (100% and 76%, respectively). In addition, trade restrictions negatively affected only some socio-economic SDG targets, specifically SDG2.1 and SDG17.11. In detail, countries with trade restrictions performed better on SDG2.1, with only a 0.3% drop on average, compared with those without trade restrictions, which dropped by 3.0%. There are two reasons for these differences. First, the purpose of trade restrictions is to maintain the domestic food supply by decreasing exports[14,25]. Second, trade restrictions disrupt the food supply chain of import-oriented countries, which cannot be self-sufficient in agriculture due to natural resource limitations, and hence face food security risks. In addition, trade

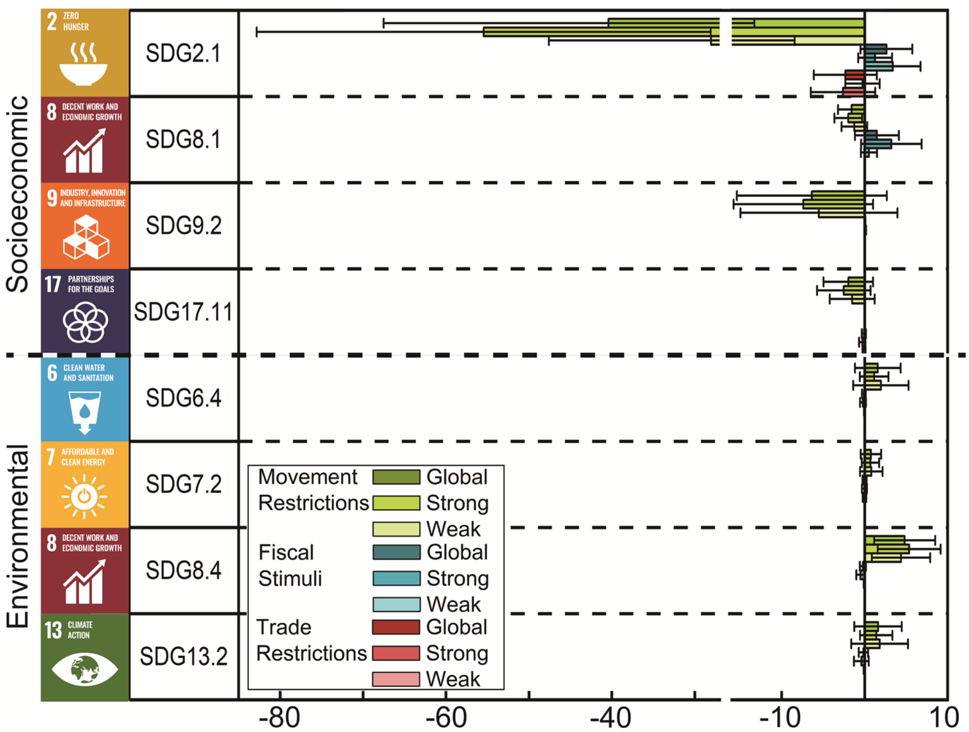

Fig. 2 Different impacts of three pandemic responses (i.e., movement restrictions, fiscal stimuli, and trade restrictions) on SDG targets. "Global" refers to the average of the selected SDG target scores over all countries. For movement restrictions and fiscal stimuli, "Strong" and "Weak" refer to the average of the selected SDG target scores over the countries whose policy intensity was higher and lower than the average level, respectively. For trade restrictions, "Strong" and "Weak" refer to the average of the selected SDG target scores over the countries that set and did not set trade restrictions, respectively. The error bars represent the standard deviation of the SDG scores. Credit (icons): the United Nations (SDG).

restrictions impeded the progress in trade globalization of the countries that implemented such restrictions. Their domestic export bans led to a global SDG17.11 score decrease of 9.3%.

Post-pandemic scenario analysis. Considering the future uncertainty of the pandemic, we designed 27 cases (see Supplementary Table 1 for details) to simulate global and national SDG progress during the post-pandemic period (from 2024 to 2030). In general, global SDG progress during the post-pandemic period was dependent on the method and extent of pandemic responses. Under the best scenario, namely, Back to Normal, where infectious diseases no longer emerged and movement restrictions were completely lifted all over the world, the global SDG score reached the highest point of 55.7 (Fig. 3a). However, the end of the pandemic did not lead to full achievement of the SDGs. Rather, the global SDG score gradually decreased by 0.1% from 2024 to 2030 under the no-response scenarios. This result means that the SDGs were not met under the traditional development model, highlighting that a new development model during the post-pandemic period will be essential to ensure that the SDGs are achieved[5,26]. Unsurprisingly, global sustainable development was worse under the New Normal and Pandemic Returns scenarios, where people faced pandemic risks and movement restrictions at moderate or strong levels; the global SDG score fell to 55.4 and 55.3 (Fig. 3b, c), respectively. The longer the duration of movement restrictions, the worse the achievement of the SDGs was due to the strong decline in SDG progress in developing countries, e.g., 0.9% and 1.0%, respectively, in the New Normal and Pandemic Returns scenarios. This result suggests an urgent need to eliminate the pandemic and lift movement restrictions as soon as possible to maintain the current SDG trajectory.

As mentioned above, global SDG progress further decreased under the New Normal scenario and Pandemic Returns scenarios. However, the trends in the SDG score varied due to the different pandemic responses. For example, under the New Normal scenario, the global SDG score remained constant at nearly 55.4 from 2024 to 2030 due to the normalized movement restrictions. Taking other response measures into account, including fiscal stimuli, trade restrictions, and their policy combinations, the global SDG score under the New Normal scenario lagged that under the Back to Normal scenario. This result means that other response measures cannot completely offset the impacts of movement restrictions. Indeed, they further disrupted global sustainable development because of the trade-off relationships between different SDG targets. Therefore, the best strategy to maintain SDG achievement under the New Normal scenario was to discontinue both fiscal stimuli and trade restrictions, with the global SDG score reaching the highest level of 55.4. A similar phenomenon also existed under the Pandemic Returns scenario, although the trend in global SDGs differed. In detail, under the Pandemic Returns scenario, the global SDG score between 2024

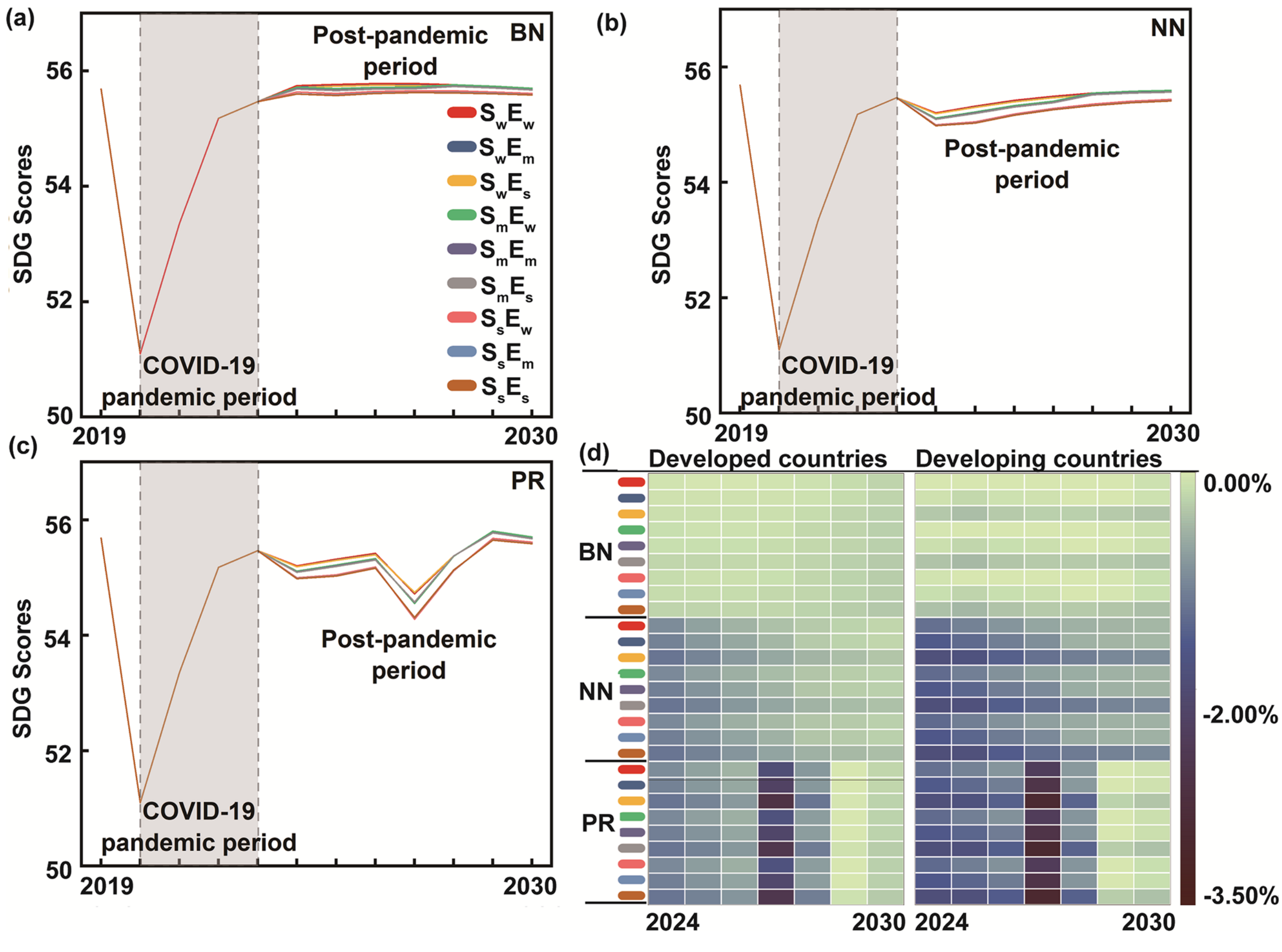

Fig. 3 Global SDG progress during the post-pandemic period. a–c Trend in SDG scores under different scenarios: **a** Back to Normal (BN), **b** New Normal (NN), and **c** Pandemic Returns (PR). **d** Relative changes in SDG scores between developed and developing countries compared with the result of "BN-S_wE_w" in 2024. "S" and "E" refer to fiscal stimuli and trade restrictions, respectively; "w", "m", and "s" refer to weak, moderate, and strong degrees of the policy level, respectively.

and 2030 showed a V-shaped trend, and its lowest point occurred in 2027, as the most severe movement restrictions were set for the emerging pandemic at that time. Since the movement restriction were gradually alleviated during the following years, the global SDG score gradually increased from 54.5 to 55.6 between 2027 and 2030. However, based on the results of nine cases under the Pandemic Returns scenario, both fiscal stimuli and trade restrictions contributed little to global sustainability. For example, fiscal stimuli accelerated socio-economic achievement of SDG2.1 and SDG8.1 by 0.2% and 1.7%, respectively, while reducing the score of the remaining SDG targets, which decreased from 0.04% to 1.5% and offset socio-economic achievement. Similarly, when trade restrictions were implemented, their impact focused on SDG2.1 and SDG17.11 negatively, and caused a 0.4% decline of the global SDG score.

Notably, the inequality between developed and developing countries was exacerbated via the widened gap in SDG progress during the post-pandemic period. In most cases, inequality in global sustainable development, as measured by relative changes in the SDG score, between developed and developing countries increased from 2024 to 2030. Among the three scenarios, this inequality was higher when pandemic risk increased and movement restrictions were more severe. For example, inequality was lowest under the Back to Normal scenario, where the relative decline for both developed and developing countries was nearly 0.2% in 2024 (Fig. 3d). However, the inequality was highest under the Pandemic Returns scenario, where the relative decline for developed countries and developing countries reached 0.7% and 1.0%, respectively. This is because developing countries lack adaptive capacity and are thus more sensitive to the socio-economic disruption caused by pandemic responses. Importantly, fiscal stimuli and trade restrictions further exacerbated the inequality caused by strict movement restrictions. Under the Pandemic Returns scenario, the relative changes in the SDG scores between developed and developing countries further increased when fiscal stimuli or trade restrictions were implemented.

Discussion

This study presents a quantitative assessment of the impacts of pandemic responses on SDG progress. Extending most previous studies which have assessed the combined impacts of the pandemic and pandemic responses or assessed sustainable development in relation to a single response policy or a single SDG, we clarified the different effects of pandemic response policies on multiple SDG targets. Our results reveal that global SDG progress was significantly impeded by COVID-19 pandemic responses from 2020 to 2023 due to the trade-offs between socio-economic and environmental targets. SDG scores in developing countries were more depressed than that in developed countries, while most socio-economic targets showed reductions which outsized the improvements evident in environmental targets. Such reductions were mainly caused by movement restrictions which were beneficial for meeting environmental targets but rapidly drove down socio-economic target scores. In contrast, fiscal stimuli were effective in mitigating socio-economic problems but this came at a significant environmental cost. Trade restrictions had the lowest negative effects on global sustainable development. Under all future pandemic trajectories, current pandemic responses were counterproductive to achieving the 2030 agenda and exacerbated inequality in sustainable development among countries, especially for socio-economic targets.

Reasons for the difference in SDG progress between developed and developing countries are twofold. First, developed countries are better able to face external shocks via policy tools, capital resources, and management experience[7]. For example, to address COVID-19, strong fiscal stimuli were predominantly implemented by developed countries such as Japan and Italy which spent about 54.9% and 30.4% of GDP, respectively, to combat COVID-19. These rates are much higher than the average level of stimulus implemented in developing countries (4.5%). Second, sustainability progress is more vulnerable in developing countries which already experience challenges related to poverty, hunger, conflict, industrialization, and environmental protection[27,28]. Because they lack complete industrial systems and are vulnerable to cascading effects from other countries along the supply chain. For example, due to the rapid decrease in foreign final demand during the COVID-19 pandemic, some African countries which delayed resource exports experienced a dramatic decline in progress towards socio-economic targets[29]. In addition, some agricultural export bans implemented by exporting countries with large market shares significantly impeded the achievement of SDG 2.1 in low-income net food importers[14].

Pandemic response measures have accelerated the achievement of some SDG targets but impeded the achievement of others[8]. This phenomenon is mainly caused by the biased influence of pandemic responses. For example, movement restrictions are beneficial for meeting environmental targets but rapidly drive down the scores of socio-economic targets. Fiscal stimuli are effective in mitigating socio-economic problems, but they do so at an environmental cost. Lacking sufficient time and complete information on the complex socio-economic and environment impacts of policy decisions, policymakers may focus on only one or two priorities such as health, economic development, or food security, rather than planning to achieve multiple SDG targets simultaneously[27,30]. By understanding the interactions between multiple targets, future pandemic responses could be modified to maximize the synergies and resolve the existing trade-offs between the SDGs, rather than solely adopt the more narrow epidemiological and public health perspective[31,32].

A post-pandemic strategy for the 2030 Agenda requires sustainable pandemic responses across all SDG targets and countries. Such a strategy should not only reduce the inequality between developed and developing countries but also resolve the trade-offs between society, the economy, and the environment. For example, although movement restrictions have proven to be effective in limiting virus transmission, they should be carefully implemented due to the significant socio-economic harm that they cause, particularly for variants with lower pathogenicity[33,34]. Developing countries should be cautious in implementing movement restrictions and improve the vaccination rate to insulate against future waves. In addition, rather than a broad lockdown of entire populations, it is necessary to develop adaptive interventions for at-risk people and consider the cascading effects on income, welfare, and food security[35]. Fiscal stimuli during a pandemic should also be revised to mitigate the trade-off between socio-economic and environmental targets. For developed countries, a pandemic offers the chance to turn the trade-offs into synergies during the recovery stage via targeted economic measures, such as boosting investment in cleaner and low-carbon industry[36,37]. For developing countries, socio-economic targets, such as SDG2.1 and SDG8.1, should be given priority in financial stimuli because they are fundamental requirements of human well-being. Thereby, the limited capital resources of developing countries could support a more flexible financial policy for improving income, employment, and food availability[11]. Based on the "leave no one behind" principle of the SDG agenda, cross-border cooperation between developing and developed countries is also necessary. Such cooperation includes not only assistance in health care but also financial and technological aid to help developing countries recover from the crisis. Trade restrictions should not be advocated as a primary choice for pandemic control, especially for major agricultural exporters, which challenge the achievement of SDG2.1 and SDG17.11.

As changes in future economic development and policy implementation could result in uncertainty in our scenario analysis of the post-pandemic period, we considered different Shared Socioeconomic Pathways (SSPs) trajectories, e.g., the sustainable road SSP1 and the rocky road SSP3 scenarios, and pandemic response measures in the uncertainty analysis. Specific methods, parameters, and results are, respectively, presented in the "Methods", Supplementary Table 1, and Supplementary Figs. 2–4. We found that the results are sensitive to the economic level and policy-induced parameters. This means if there are more strict response measures to future emerging pandemic, the achievement of global sustainability and its inequality will be worse. These results not only align with our previous conclusion, but can also verify the robustness of the AMRIO model. We also found that the negative effects of pandemic responses on sustainable development can be effectively alleviated by a more sustainable and higher level of economic development which might be a potential solution to achieve the 2030 agenda with pandemic risks.

There are also some limitations to our work. First, we selected only eight SDG targets in this study due to data and method limitations, rather than all issues of sustainability such as unemployment and health security. Hence, while this research provides a multi-dimensional assessment of global SDGs progress and a methodological foundation for further research, this work still offers only a partial coverage of the SDGs. Second, this study does not consider the changes of economic structure, production efficiency, and technology, due to a homogeneity assumption within the AMRIO mode. Therefore, there are potential shortcomings of this model to fit in with the reality during the long term, but it will not affect the main conclusion of this study. Because our model does not aim to accurately project future SDG achievements but clarify mixed impacts from different scenarios and policy measures to guide global and national sustainability and public health measures. Finally, we also simplified the policy effect in the model due to limited temporal, regional, or sectoral information presented in the GTAP-MRIO table and IMF report[38,39]. For example, we did not take medical product export bans, such as masks and drugs, into account. We cannot evaluate seasonal pandemic measures and sub-national level indicators based on an annual global input–output table. We only considered the fiscal stimuli for certain integrated sectors, including agriculture, energy, manufacturing, construction, services, medical, and household final demand. Future studies could consider updated data and other economic models such as a computable general equilibrium model to predict future SDG progress.

Despite these uncertainties and limitations, our research framework lays a foundation to further explore the impacts of pandemic response measures on sustainable development across multiple dimensions. Our results suggest that pandemic responses will challenge our ability to meet the United Nations 2030 Agenda. Current response measures should be more targeted and better aligned with sustainable development, which requires a deep understanding of the potential trade-offs between SDG targets and the rising inequality between nations. Global scientists, policymakers, and leaders should also learn from the COVID-19 crisis to raise awareness of the most vulnerable countries (i.e., African countries) and the hardest hit indicators (i.e., food security) which need the greatest support to progress in the United Nations Decade of Action towards the SDGs.

Methods

Adaptive multi-regional input–output model. We used a global adaptive multi-regional input–output (AMRIO) model to evaluate the impacts of COVID-19 pandemic responses on the global supply chain and their cascading effects on the sustainable development of nations. This model has been previously used to quantify the economic loss, resource consumption, and environmental pollution derived from disasters such as pandemics and flood[6,9]. Its advantage is in accounting for interactions between supply and demand at the sectoral level based on a global input–output table, while adjusting to short-term or time-varying shocks from disaster impacts[9,40]. We referred to the model presented by Shan et al.[9] and extended the pandemic responses to three widely used measures: movement restrictions, fiscal stimuli, and trade restrictions during the pandemic and post-pandemic periods. We assessed progress towards global sustainable development by quantifying the impacts of pandemic responses of each individual country. A complete description with the full set of equations is presented in the Supplementary Methods.

Pandemic responses are considered to disrupt the balance between production and consumption across the global supply chain, which consists of different countries and industries. In a country, there are two types of agents, namely households and industries, which devote themselves both to production and consumption activities. We assumed the households of each country had a fixed bundle of consumption and supply labor for domestic production among various industries. We assumed that each industry produced unique goods or services with essential primary inputs, i.e., capital and labor, as well as intermediate inputs from other industries. If pandemic responses have not occurred, the output of each industry was able to meet the demand of households (final demand) and other industries (intermediate input). We considered three kinds of pandemic responses for COVID-19, i.e., movement restrictions, fiscal stimuli, and trade restrictions.

Movement restrictions have significant impacts both on the production and consumption sides. On the production side, these measures have constrained labor supply and product transformation[6]. On the consumption side, these measures have caused a dramatic fall in final demand, particularly among the entertainment and tourism sectors[41]. Hence, we set different levels of labor shortage, product transformation, and household consumption among various sectors. Fiscal stimuli were also considered in our model, as a common disaster response to promote economic recovery and social stability[42]. Based on previous studies, most stimuli measures were designed to increase cash flow to household necessities and support industrial development[9,43]. Thus, we assumed fiscal stimuli would increase the economic size of targeted agents, i.e., households and certain sectors, according to the country-specific plan. Furthermore, we considered the impact of trade restrictions on the global market because it has directly exacerbated the imbalance between supply and demand since the outbreak of the pandemic. Due to the limitation of data, we only took export bans on agricultural products into account by reshaping the cross-regional trade flows, rather than all kinds of trade restrictions in this study. Specifically, if a certain kind of product is prohibited from trading between two countries, we set the trade flow of this product to zero.

To assess the impacts of pandemic responses, we provided a hypothetical business-as-usual (BAU) scenario, assuming that the COVID-19 pandemic never emerged. Under the BAU, socio-economic activities were unaffected by pandemic responses and maintained recent historical trajectories according to projections under the middle-of-the-road from SSP2[44–46]. Against this counterfactual, we evaluated the separate and combined impacts of three pandemic responses against multiple indicators of sustainability.

Scenario settings. To distinguish the impact between the pandemic and post-pandemic period, we set 2023 as the break point, according to WHO's expectation of the end of COVID-19 and related response measures[21]. We took 2020–2023 as the pandemic period, during which the pandemic responses (i.e., movement restrictions, fiscal stimuli, and trade restrictions) were implemented according to existing policies, data, and literature. For instance, we set the duration and strictness of movement restrictions using Google Community Mobility Reports and Oxford COVID-19 Government Response Tracker during the pandemic period[47,48], where the level of labor shortage, transportation disruption, and final demand of certain industries were reduced accordingly. Google Community Mobility Reports provide mobility data in the workplace and residential areas for nearly all countries except China, where we used the national migration scale index from the Baidu Qianxi dataset to indicate China's policy strictness[49]. In addition, we set an expiration date of national movement restrictions according to the real policy validity period from Oxford COVID-19 Government Response Tracker. Due to the Google database ceasing updates on 15 October 2022, we had to fill the missing mobility data for countries which had not canceled movement restrictions by that time. Hence, we made a linear projection based on an assumption that the mobility level will linearly recover to pre-pandemic levels by the expiration date. Fiscal stimuli was implemented in the model by increasing domestic production and consumption of eight integrated sectors, with the share of growth in these eight sectors raised according to the information from the International Monetary Fund[38]. A full description of related policy and data is presented in Supplementary Table 2. We set the trade restriction duration and affected products based on announced trade bans which usually aimed to bolster domestic food security by restricting the export of agricultural products. We collected data on export bans on agricultural goods from the International Trade Center[50]. We extracted information about the trade ban time period and affected products to re-calculate the trade flows in the AMRIO model, see Supplementary Table 3 for detail.

We took 2024–2030 as the post-pandemic period where the impact of three kinds of pandemic responses was assessed, characterized by various response levels. Due to uncertainty in future risk posed by COVID-19, we referred to the narrative scenarios from the projection of WHO and correspondently designed three different scenarios[51]: (1) the pandemic ends and life is back to normal (Back to Normal); (2) the pandemic coexists with humans and induces a new normal (New Normal); (3) the pandemic returns and shocks again (Pandemic Returns). Thus, we assumed that movement restrictions were completely lifted, seasonally occurred, and strictly re-implemented again during the seven years under the Back to Normal, New Normal, and Pandemic Returns scenarios, respectively (Supplementary Table 4). We designed three different levels of fiscal stimuli and trade restrictions for supporting socio-economic development during the period: strong, moderate, and weak (Supplementary Table 1). In total, we explored 27 cases to provide a comprehensive insight into potential future post-pandemic trajectories and the impacts across the SDGs. Rather than make an accurate projection on SDG achievements, our aim was to compare "what if" outcomes of these different scenarios for the SDGs and obtain policy implications for future pathways towards the 2030 agenda.

Calculation of SDG indicators, targets, and scores. We selected SDG targets based on the following two criteria: (1) the targets are conceptually clear and have an established indicators and methodologies according to *Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development*[52]; and (2) the data for quantifying indicators and performance against targets matches with the input–output table and homogeneity assumptions applied in the AMRIO model. Via this process we selected eight targets and classified them into (four) socio-economic targets: SDG2.1, SDG8.1, SDG9.2, and SDG17.11, and (four) environmental targets: SDG6.4, SDG7.2, SDG8.4, and SDG13.2. Targets are summarized in Table 1 along with basic implications and representative indicators.

We evaluated the pandemic response impacts on the eight SDG targets by calculating representative indicators under different circumstances. Consistent with previous studies[6,9], we assumed that the economic structure and technology level is unlikely to change significantly within such a short time. In other words, the global supply chain was considered to remain constant during the study period unless pandemic responses occurred. Under each scenario, we directly obtained some economic consequences for each country, including GDP, manufacturing value-added, and export value to evaluate SDG8.1, SDG9.2, and SDG17.11, respectively, based on simulation results from AMRIO. We quantified environmental indicators including water use for SDG6.4, energy consumption for SDG7.2, material consumption for SDG8.4, and total greenhouse emission emissions for SDG 13.2 based on their production-based environmental footprint, referring to their consumption or emissions intensity multiplied by economic output (shown in Eq. (1)).

$$EF_{i,r}^{t} = intensity_{i,r}^{t} \times output_{i,r}^{t} \quad (1)$$

where $EF_{i,r}^{t}$ indicates a certain environmental footprint, such as energy consumption or greenhouse gas emissions, the subscripts i and r indicate sector and region, respectively, while t indicates year. *intensity* indicates the sectoral intensity of certain resource consumption or pollution emissions per unit of economic output (*output*). The emissions and consumption intensities were obtained from the Global Trade Analysis Project (GTAP) and Eora26 databases[39,53,54]. For evaluating SDG2.1, we used the prevalence of undernourishment calculated via the widely used method from FAO[55].

In addition, there are four negative targets, such as greenhouse gas emissions, which need to be reduced to achieve sustainable development, and four positive targets, such as economic growth, which need to be increased. In order to obtain a comparable score for these targets, we standardized them on a scale of 0 to 100 based on the method of Xu et al.[2]. This measure enabled us to quantify progress toward sustainability at the national and global level in terms of each target (see the Supplementary Methods for detail): the larger the country's SDG indicator score is, the better the progress and performance. To track integrated SDG progress at national and global level, we gave equal weight to each target and country, since all committed countries are required to achieve the full set of targets by 2030 following the principle of "leave no one behind". Hence, the SDG score was calculated as the mean indicator score across eight targets (at national level) and all countries (at global level). Similarly, an increasing score over the study period reflected a positive trend towards SDG achievement.

Uncertainty analysis. To identify the uncertainties due to the impacts of economic development and response measures during post-pandemic period, we ran a series of sensitivity simulations with AMRIO model. We chose the different development trajectories from the SSPs database, e.g., the sustainable road SSP1 and the rocky road SSP3, which, respectively, indicates a higher and lower economic level than the middle-of-the-road SSP2. For both SSP1 and SSP3 trajectories, we simulated 27 cases of pandemic responses to three future pandemic scenarios, e.g., Back to Normal, New Normal, and Pandemic Returns. The policy ranges are summarized in Supplementary Table 1. Detailed results for the uncertainty analysis are presented in Supplementary Figs. 2–4.

Data. For AMRIO model construction, we used a global multi-regional input–output table from the GTAP 10 database[39], which presents the primary input, intermediate production, and final demand of 65 sectors among countries or regions in 2014 (Supplementary Table 5). For SDG score calculation, we collected national environmental data in 2014 and the latest year, as well as socio-economic data projected between 2020 and 2030. We collected five kinds of environmental and consumption accounts for 2014 to match the input–output table, which includes greenhouse gas emission and energy consumption from GTAP[39,54], water use, and material consumption from Eora26[53], agricultural products consumption from FAO[56]. We then collected the latest data and calculated their proportion between recent years and 2014 to estimate selected indicators during the study period based on the assumption of technology homogeneity. In detail, the latest environmental data consisted of greenhouse gas emissions and energy consumption from IEA in 2018[57], water use and agricultural product consumption from FAO in 2018[56,58], and material use from UN-IRP in 2018[59]. The socio-economic data included the projected GDP and population of each country between 2020 and 2030 from the SSPs Database[44–46]. Because some country-level data was unavailable, our final dataset consisted of 113 countries and regions (Supplementary Table 6).

Data availability

All datasets analyzed in this study are publicly available as referenced within the article and in the Supplementary Information. Global multi-regional input–output table is from the GTAP 10 database (https://www.gtap.agecon.purdue.edu/databases/v10/index.aspx); movement restrictions are from Google Community Mobility Reports (https://www.google.com/covid19/mobility/), Oxford COVID-19 Government Response Tracker (https://github.com/OxCGRT/covid-policy-tracker), and Baidu Qianxi dataset (https://qianxi.baidu.com/); fiscal stimuli is from International Monetary Fund (https://www.imf.org/en/Topics/imf-and-covid19/Policy-Responses-to-COVID-19); trade restrictions are from International Trade Center (https://www.macmap.org/en/covid19). Other processed data are available at figshare: https://doi.org/10.6084/m9.figshare.23521992.

Code availability

All codes used in this study are available on figshare (https://doi.org/10.6084/m9.figshare.20887966).

Received: 10 January 2023; Accepted: 26 June 2023;
Published online: 12 July 2023

References

1. The United Nations. *Remarks to High-Level Political Forum on Sustainable Development.* https://www.un.org/sg/en/content/sg/speeches/2019-09-24/remarks-high-level-political-sustainable-development-forum (2019).
2. Xu, Z. et al. Impacts of international trade on global sustainable development. *Nat. Sustain.* **3**, 964–971 (2020).
3. The United Nations. *Sustainable Development Report 2021. Cambridge University Press* https://www.cambridge.org/au/academic/subjects/economics/economic-development-and-growth/sustainable-development-report-2021?format=HB&isbn=9781009098915 (2021).
4. The United Nations. *Sustainable Development Report 2022. Cambridge University Press* https://www.cambridge.org/au/academic/subjects/economics/economic-development-and-growth/sustainable-development-report-2022?format=PB&isbn=9781009210034 (2022).
5. Naidoo, R. & Fisher, B. Sustainable Development Goals: pandemic reset. *Nature* **583**, 198–201 (2020).
6. Guan, D. et al. Global supply-chain effects of COVID-19 control measures. *Nat. Hum. Behav.* **4**, 577–587 (2020).
7. Ibn-Mohammed, T. et al. A critical review of the impacts of COVID-19 on the global economy and ecosystems and opportunities for circular economy strategies. *Resour. Conserv. Recycl.* **164**, 105169 (2021).
8. Lenzen, M. et al. Global socio-economic losses and environmental gains from the coronavirus pandemic. *PLoS ONE* **15**, e0235654 (2020).
9. Shan, Y. et al. Impacts of COVID-19 and fiscal stimuli on global emissions and the Paris Agreement. *Nat. Clim. Chang.* **11**, 200–206 (2021).
10. Shuai, C. et al. Quantifying the impacts of COVID-19 on Sustainable Development Goals using machine learning models. *Fundam. Res.* https://doi.org/10.1016/j.fmre.2022.06.016 (2022).
11. Elavarasan, R. M. et al. Impacts of COVID-19 on Sustainable Development Goals and effective approaches to maneuver them in the post-pandemic environment. *Environ. Sci. Pollut. Res.* **29**, 33957–33987 (2022).
12. Maire, J. et al. How different COVID-19 recovery paths affect human health, environmental sustainability, and food affordability: a modelling study. *Lancet Planet. Heal.* **6**, e565–e576 (2022).

13. Laborde, D., Herforth, A., Headey, D. & de Pee, S. COVID-19 pandemic leads to greater depth of unaffordability of healthy and nutrient-adequate diets in low- and middle-income countries. *Nat. Food* **2**, 473–475 (2021).
14. Falkendal, T. et al. Grain export restrictions during COVID-19 risk food insecurity in many low- and middle-income countries. *Nat. Food* **2**, 11–14 (2021).
15. Zhang, Y. et al. The perceived effectiveness and hidden inequity of postpandemic fiscal stimuli. *Proc. Natl. Acad. Sci. USA* **119**, 1–9 (2022).
16. Ranjbari, M. et al. Three pillars of sustainability in the wake of COVID-19: a systematic review and future research agenda for sustainable development. *J. Clean. Prod.* **297**, 126660 (2021).
17. Shao, S., Feng, K., Shan, Y. & Chen, S. How do China's lockdown and post-COVID-19 stimuli impact carbon emissions and economic output? Retrospective estimates and prospective trajectories. *iScience* **25**, 104328 (2022).
18. Nundy, S., Ghosh, A., Mesloub, A., Albaqawy, G. A. & Alnaim, M. M. Impact of COVID-19 pandemic on socio-economic, energy-environment and transport sector globally and sustainable development goal (SDG). *J. Clean. Prod.* **312**, 127705 (2021).
19. Phillips, C. A. et al. Compound climate risks in the COVID-19 pandemic. *Nat. Clim. Chang.* **10**, 586–588 (2020).
20. Wang, D. et al. Supply chains create global benefits from improved vaccine accessibility. *Nat. Commun.* **14**, 1569 (2023).
21. Adam, D. When will COVID stop being a global emergency? *Nature* **614**, 201–202 (2023).
22. The United Nations. *SDG Indicators Database*. https://unstats.un.org/sdgs/dataportal/database (2023).
23. International Energy Agency. *Greenhouse Gas Emissions from Energy Data Explorer*. https://www.iea.org/data-and-statistics/data-tools/greenhouse-gas-emissions-from-energy-data-explorer (2021).
24. Hartono, D., Yusuf, A. A., Hastuti, S. H., Saputri, N. K. & Syaifudin, N. Effect of COVID-19 on energy consumption and carbon dioxide emissions in Indonesia. *Sustain. Prod. Consum.* **28**, 391–404 (2021).
25. World Trade Organization. WTO members resume agriculture negotiations following COVID-19 pause. https://www.wto.org/english/news_e/news20_e/agng_25sep20_e.htm (2020).
26. Bryan, B. A., Hadjikakou, M. & Moallemi, E. A. Rapid SDG progress possible. *Nat. Sustain.* **2**, 999–1000 (2019).
27. Barbier, E. B. & Burgess, J. C. Sustainability and development after COVID-19. *World Dev.* **135**, 105082 (2020).
28. Shulla, K. et al. Effects of COVID-19 on the Sustainable Development Goals (SDGs). *Discov. Sustain.* **2**, 15 (2021).
29. Fagbemi, F. COVID-19 and sustainable development goals (SDGs): An appraisal of the emanating effects in Nigeria. *Res. Glob.* **3**, 100047 (2021).
30. Tan, M. M. J. et al. Assessing the role of qualitative factors in pandemic responses. *BMJ* **375**, e067512 (2021).
31. Marco, M. D. et al. Sustainable development must account for pandemic risk. *Proc. Natl. Acad. Sci. USA* **117**, 3888–3892 (2020).
32. Kroll, C., Warchold, A. & Pradhan, P. Sustainable Development Goals (SDGs): Are we successful in turning trade-offs into synergies? *Palgrave Commun* **5**, 140 (2019).
33. World Health Organization. *Interview with WHO Chief Scientist Dr Soumya Swaminathan: Mobilizing Evidence in Health Emergencies*. https://www.who.int/news/item/07-11-2021-interview-with-who-chief-scientist-dr-soumya-swaminathan-on-mobilizing-evidence-in-health-emergencies (2022).
34. Bálint, G., Vörös-horváth, B. & Széchenyi, A. Omicron: increased transmissibility and decreased pathogenicity. *Signal Transduct. Target. Ther.* **7**, 151 (2022).
35. Lenzer, J. Covid-19: Experts debate merits of lockdowns versus 'focused protection'. *BMJ* **371**, m4263 (2020).
36. Wan, D., Xue, R., Linnenluecke, M., Tian, J. & Shan, Y. The impact of investor attention during COVID-19 on investment in clean energy versus fossil fuel firms. *Financ. Res. Lett.* **43**, 101955 (2021).
37. Tian, J., Yu, L., Xue, R., Zhuang, S. & Shan, Y. Global low-carbon energy transition in the post-COVID-19 era. *Appl. Energy* **307**, 118205 (2022).
38. International Monetary Fund. *Policy Responses to COVID-19*. https://www.imf.org/en/Topics/imf-and-covid19/Policy-Responses-to-COVID-19 (2021).
39. Aguiar, A., Chepeliev, M., Corong, E. L., McDougall, R. & van der Mensbrugghe, D. The GTAP data base: version 10. *J. Glob. Econ. Anal.* **4**, 1–27 (2019).
40. Hallegatte, S. An adaptive regional input-output model and its application to the assessment of the economic cost of Katrina. *Risk Anal* **28**, 779–799 (2008).
41. Soga, M., Evans, M. J., Cox, D. T. C. & Gaston, K. J. Impacts of the COVID-19 pandemic on human–nature interactions: Pathways, evidence and implications. *People Nat* **3**, 518–527 (2021).
42. Hepburn, C., O'Callaghan, B., Stern, N., Stiglitz, J. & Zenghelis, D. Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change? *Oxford Rev. Econ. Policy* **36**, S359–S381 (2020).
43. McElwee, P. et al. Ensuring a post-COVID economic agenda tackles global biodiversity loss. *One Earth* **3**, 448–461 (2020).
44. Crespo Cuaresma, J. Income projections for climate change research: a framework based on human capital dynamics. *Glob. Environ. Chang.* **42**, 226–236 (2017).
45. KC, S. & Lutz, W. The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100. *Glob. Environ. Chang.* **42**, 181–192 (2017).
46. Riahi, K. et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Chang.* **42**, 153–168 (2017).
47. Google. *Google Community Mobility Reports*. https://www.google.com/covid19/mobility/index.html?hl=en (2022).
48. Oxford COVID-19 Government Response Tracker. *University of Oxford*. https://www.bsg.ox.ac.uk/research/covid-19-government-response-tracker (2023).
49. Baidu Qianxi. Daily Migration index. https://qianxi.baidu.com/qianxi.baidu.com/ (2023).
50. International Trade Centre. *COVID-19 Temporary Trade Measures*. https://www.macmap.org/covid19 (2021).
51. World Health Organization. *Imagining the Future of Pandemics and Epidemics: A 2022 Perspective* (2022).
52. The United Nations. *Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development* (The United Nations, 2021).
53. Lenzen, M., Moran, D., Kanemoto, K. & Geschke, A. Building Eora: a global multi-region input-output database at high country and sector resolution. *Econ. Syst. Res.* **25**, 20–49 (2013).
54. Chepeliev, M. Development of the air pollution database for the GTAP 10A data base development of the air pollution database for the GTAP data base version 10A. *Gtap Res. Memo.* **33**, 1–40 (2020).
55. Food and Agriculture Organization. *FAO Methodology for the Measurement of Food Deprivation* (2008).
56. Food and Agriculture Organization. *FAOSTAT Statistics Database*. https://www.fao.org/faostat/en/#data (2022).
57. International Energy Agency. *IEA Energy and Carbon Tracker 2020*. https://www.iea.org/data-and-statistics/data-browser?country=WORLD&fuel=Energysupply&indicator=TESbySource (2020).
58. Food and Agriculture Organization. *AQUASTAT*. https://www.fao.org/aquastat/statistics/query/index.html (2021).
59. UN-IRP. *Global Material Flows Database*. From UN International Resources Panel. http://www.resourcepanel.org/global-material-flows-database.%0A (2018).

Acknowledgements
We thank the United Nations for making the SDG icons available (www.un.org/en/sustainable-development-goals). This study is financially supported by the National Natural Science Foundation of China (42077060 and 41877070) and National Foundation of China Scholarship Council (Grant No. 202106760040).

Author contributions
C.L. drafted the manuscript. Z.D. and C.L. did the data analysis and visualization. Z.W. and Z.S. conceived the study. Y.H., B.B., Z.W., and Z.D. reviewed and edited the manuscript. L.W., S.Y., and Z.W. designed the methodology. W.L. collected the data. B.B. and Z.W. supervised all the work.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-023-00914-2.

Correspondence and requests for materials should be addressed to Zhen Wang or Zhihua Shi.

Peer review information *Communications Earth & Environment* thanks Daoping Wang and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Niheer Dasandi and Aliénor Lavergne. A peer review file is available.