ARTICLE

Check for updates

Progress towards the Sustainable Development Goals has been slowed by indirect effects of the COVID-19 pandemic

Haixia Yuan[1,7], Xiaoming Wang[2,3,7], Lei Gao [4], Tao Wang [1✉], Bingsheng Liu[1], Dongping Fang[5] & Yi Gao[6]

The COVID-19 pandemic has undermined the ability of many countries to achieve the Sustainable Developments Goals (SDGs) by 2030. Here, we systematically assess the likely impacts of the pandemic on progress towards each SDG by 2030 at global, regional and national scales. In our analysis, we account for the social and economic shocks triggered by COVID-19 and their relative impacts on the SDGs. We also analyze the interconnections between SDG indicators during the pandemic to assess the indirect cascading effects of COVID-19 on the SDGs. We find that these indirect effects slowed progress much more than the direct initial disruptions. Globally, poverty eradication (SDG 1) is most affected by the pandemic. Regionally, SDG progress has been set back most in Latin America and the Caribbean, South Asia, the Middle East and North Africa and Sub-Saharan Africa. We suggest that for high and upper-middle-income countries a focus on reducing inequality (SDG 10) would be most beneficial, whereas for low-income and lower-middle-income countries industry, innovation, and infrastructure (SDG 9) are a priority in the post-COVID-19 phase.

[1] School of Public Policy and Administration, Chongqing University, Chongqing, China. [2] Department of Civil Engineering, Monash University, Clayton, VIC 3800, Australia. [3] The State Key Laboratory of Cryosphere Science, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Science, Lanzhou, Gansu, China. [4] Commonwealth Scientific and Industrial Research Organization (CSIRO), Waite Campus, Urrbrae, SA, Australia. [5] School of Civil Engineering, Tsinghua University, Beijing, China. [6] China Xiong'an Group Ecological Construction Investment Co., Ltd, Baoding, Hebei, China. [7] These authors contributed equally: Haixia Yuan, Xiaoming Wang. ✉email: tao.wang@cqu.edu.cn

When the SDG Decade of Action[1] began in 2020, COVID-19 broke out and became a global pandemic, significantly impacting progress towards the SDGs[2–4] that was already faltering, even before COVID-19[5,6]. It further undermined countries' ability to achieve them by 2030[3,7]. Failing to achieve the SDGs will result in a harmful effect on the well-being of billions of people and aggravate existing socioeconomic and environmental crises[8]. Therefore, it is vital to understand how the track of the world towards the SDGs was altered by the pandemic, identify the gaps and put forwards targeted global efforts to reaccelerate the pace to rescue the 2030 Agenda from failing[8,9].

The impacts of the COVID-19 pandemic on global SDG progress are complex and are considered to be uncertain, long-lasting[10], multifaceted, and difficult to assess. The intricate interconnections among the seventeen SDGs further compound their complexity[11–15]. The pandemic has had apparent impacts on various aspects of the SDGs, including the economy[16,17], health[18–20], reduced inequality[17,21], agriculture and food[22–24], education[25], the environment[26–29], and social justice[30]. However, the focus of studies on the impacts of COVID-19 has been on individual or a few SDGs, and most of them have lacked a systematic approach to assess pandemic impacts on all SDGs from the scale of countries to regions and the globe[4,9]. This hinders the development of more effective and targeted investment to reverse the setbacks caused by the COVID-19 pandemic.

Therefore, we aim to quantify the impacts of the pandemic on the progress towards each SDG by 2030 for each of the 163 countries that have recorded their progress thus far. It will help us understand how progress towards the SDGs was retarded by the pandemic at the global and regional scales, as well as in countries at different levels of economic development. In this regard, we establish an approach that reconstructs the entire process of the SDGs in response to COVID-19 impacts, as described in Fig. 1.

We assume that the COVID-19 impacts on the SDGs are induced by the shocks that are represented by the initial disturbances caused by COVID-19, largely in terms of increased mortality and morbidity, economies and activities slowed by lockdowns, and depleted public resources. The COVID-19 impact on every SDG in each country is a combined effect of shock loss and growth delay loss, as shown in Fig. 1. We obtain the shock loss for every SDG in each country by applying the country's status to adjust the nominal impacts on each SDG, which reflects general perceptions of the direct impacts of COVID-19 shocks on the basis of the extensive literature related to COVID-19 impacts on each SDG indicator and indirect impacts caused by cascading effects due to interconnections among the SDGs. A country's status includes what each country has achieved in terms of SDG progress before the pandemic and covers COVID-19 severity in each country and the country's ability to respond to COVID-19 shocks measured on the impact severity index provided in the Global COVID-19 Index (GCI)[31]. The interconnections are quantified by a matrix among 17 SDGs represented by 92 indicators from 2000 to 2019, for a total of 3933 indicator pairs for all 193 UN member countries. We estimate the growth delay loss for every SDG in each country by considering the deceleration and then recovery of SDG progress, which depends on the resilience of each country in recovering from COVID-19 impacts represented by both the GCI Recovery Index and Severity Index[31]. The impact of COVID-19 on global, regional and national progress towards every SDG is then measured by a population-weighted aggregation of shock loss and growth delay loss in each country.

Given both changes and the pre-COVID-19 gap in meeting the SDGs, we finally evaluate the post-COVID-19 risk of countries failing to achieve their SDGs by 2030 in association with the income groups to which their economies are assigned, as defined by the World Bank[32]. More details about the approach and relevant data can be found in the Methods and Supplementary Data 1.

The findings have shown that the progress towards achieving the SDGs has been greatly impeded, not only by the direct impact, but also more by the indirect impacts of the COVID-19 pandemic. They also highlight the different risk profiles among countries at different income levels, in addition to substantial regional differences. This provides a basis for international bodies (e.g. United Nations), government, and all relevant decision-makers, as well as researchers to use the application of the methodological process to understand the impacts of COVID-19 on SDG progress at global, regional, and national scales so they can identify options and address the development gaps, most importantly, recover from the impacts, and advance the 2030 SDG agenda.
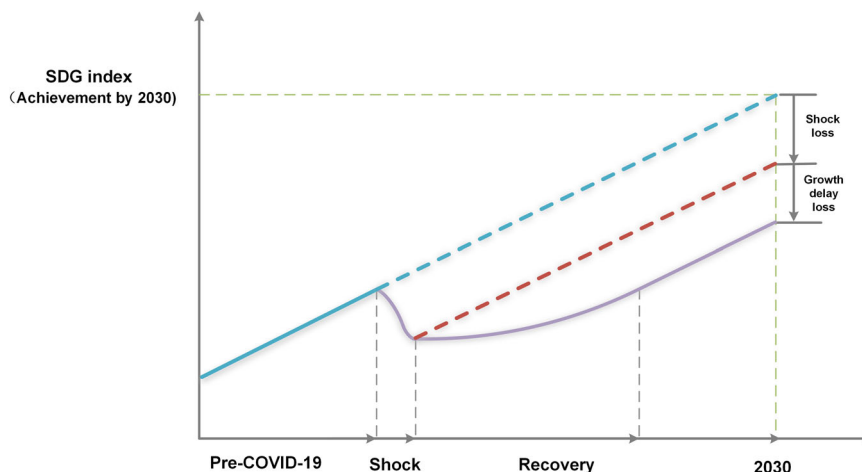

Fig. 1 Conceptual description of the process of COVID-19 impacts on SDG progress by 2030. The blue line represents the progress towards SDGs without COVID-19 impacts. The purple line shows the progress following the impacts. The impacts are described by the sum of shock loss and growth delay loss in recovery, leading to an eventual return to the pre-COVID progress rate (i.e., the position indicated by the gray dashed line in the vertical direction). The degree of progress loss by shock and growth delay depends on the resilience of relevant countries, which affects their capacity to resist the COVID-19 shocks and the speed of recovery after the shock (see Methods).
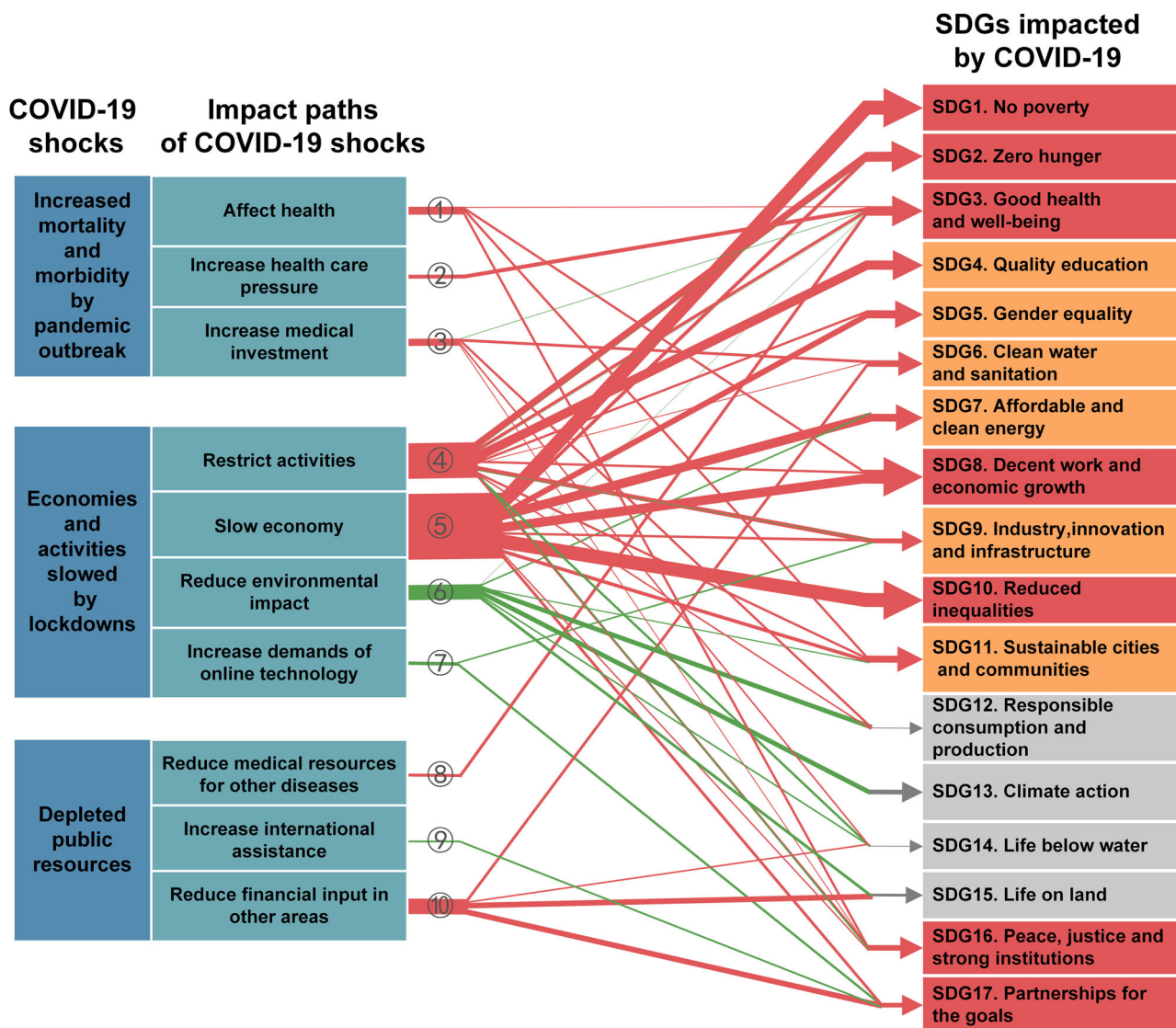
Fig. 2 Nominal direct impacts of COVID-19 on the SDGs. The nominal direct impact on each SDG of 17 in total can be caused through ten specific paths aligned with three initial COVID-19 shocks. The shocks are represented by increased mortality and morbidity as a result of the pandemic outbreak, economies and activities slowed by lockdowns, and depleted public resources, which are linked to 10 additional specific representations in connection with the SDGs. The thickness of the lines and the size of the arrows represent the degree of global impact (see more details in Methods, Supplementary Note 1 and Supplementary Data 1). The red color represents negative impacts, while the green indicates positive impacts and the gray means uncertain. For the SDGs, red represents the goal incurring highly negative impacts, orange represents mixed or moderate negative impacts, and gray implies uncertain overall impacts.

Results

COVID-19 impacts on global progress towards the SDGs by 2030. First, we define the nominal direct impacts representing the perceptions of the direct consequences of COVID-19 shocks acting on specific SDGs via the impact paths, as shown in Fig. 2 (More details see the Methods). As a result, we find that the COVID-19 shocks adversely impacted 13 of the 17 SDGs via approximately ten paths. Among them, the goals of eradicating poverty (SDG 1), achieving zero hunger (SDG 2), good health and well-being (SDG 3), decent work and economic growth (SDG 8) and reduced inequality (SDG 10) are the top five that received the greatest direct impacts.

Regardless of the immediate benefit of strengthening climate action (SDG 13) due to reduced economic activities, COVID-19 has generally had negative impacts on all other SDGs to various degrees (Fig. 2). The pandemic has generally been understood not only as a health emergency but also as a socioeconomic crisis.

Additionally, COVID-19 has compromised the development of the SDGs in three main ways: restricted activities, slowed economies, and reduced investment in areas other than health systems. Nevertheless, approximately 26% of the targets in SDGs 2, 3, 7, 9, and 11–17 presented immediate opportunities through reduced environmental impacts, increasing demand for technology, and enhanced international assistance, in addition to more investment in healthcare.

The nominal indirect impacts induced by the cascading effects of COVID-19 on the 17 SDGs through their interconnections are estimated and represented by Fig. 3 (see more details in Methods). The indirect impacts are most severe on SDGs 1 (no poverty), 9 (industry, innovation and infrastructure), 3 (good health and well-being), 4 (quality education), 7 (affordable and clean energy), and 11 (sustainable cities and communities), with effects up to more than thirty times greater than the direct impacts on average.
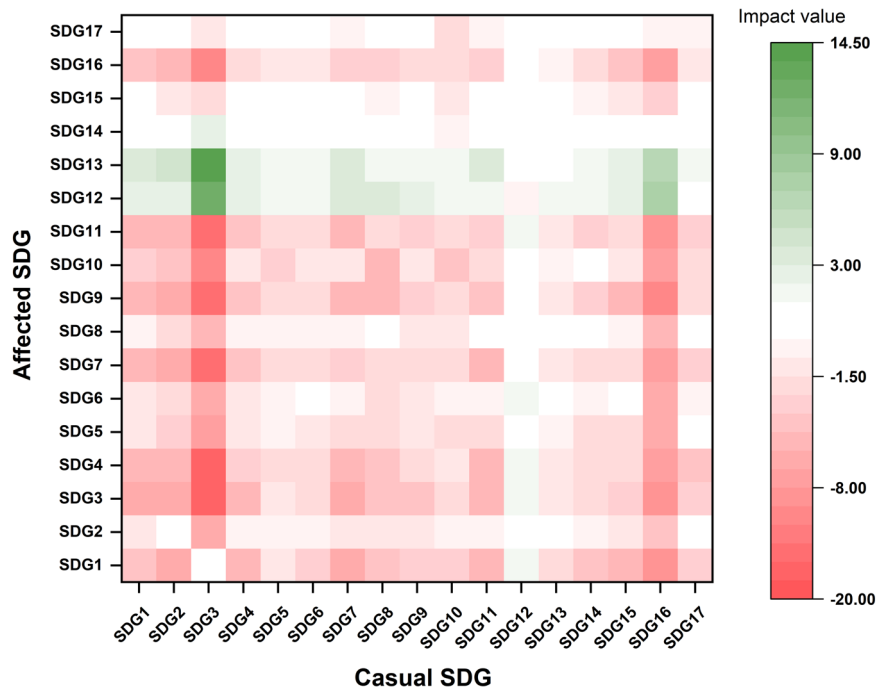
Fig. 3 Matrix of nominal indirect impacts of COVID-19 on the SDGs. Each grid represents the degree of a cascading effect from one SDG to another, represented by the causal SDG in the row and the affected one in the column; the nominal indirect impact value is estimated on the basis of the nominal direct impacts of COVID-19 on one SDG and its interactions with others (see more details in Methods). The color scale shows the value of nominal indirect impacts of COVID-19 from the causal SDG in the row to the affected one in the column. The green grid reflects positive influences, while the red reflects negative influences.

Overall, the nominal indirect impacts are seven times greater than the nominal direct impacts on average, highlighting the hidden ramifications of the pandemic. Interestingly, the main causes of the nominal indirect impacts on the SDGs, are the COVID-19 shocks on SDGs 3 (good health and well-being) and 16 (peace, justice and strong institutions). It is particularly evident for the six goals, SDGs 1, 3, 4, 7, 9 and 11. The average nominal indirect impact of SDGs 3 and 6 on those six goals is approximately seven times more than the average from all of the goals. Some SDGs, such as responsible consumption and production (SDG 12), climate action (SDG 13) and life below water (SDG 14), are related to environmental protection. It is worth noting that these goals often act in trade-offs with other development goals[12,13]. While COVID-19 generally produced negative impacts on the SDGs, it simultaneously had positive indirect effects on some goals, such as SDGs 12 and 13.

The shock loss of each country's progress towards every SDG is then estimated by adjusting the nominal impact, and the growth delay loss during recovery is also evaluated (see Methods). The beneficial effects of COVID-19 impacts on SDGs 12, 13 and 14 were largely relinquished during the recovery[9,10,33,34]. Therefore, it is assumed that the progress towards those SDGs resumed after the shocks, and this progress would hardly be affected. As a result, they are not included in the impact analysis.

By aggregating the shock loss and growth delay loss of all countries weighted by their population, the degree of COVID-19 impacts on global progress towards the SDGs can then be described as shown in Fig. 4. The goal of no poverty (SDG 1) is considered to be the most affected, as it has the highest direct and indirect shock loss as well as growth delay loss second only to that of SDG 9. The main reason is that COVID-19 threatens to increase extreme poverty (i.e., SDG 1.1 and 1.2) in many countries which mainly due to economic lockdown caused by the pandemic[35], and the high level of connectivity that exists with

other goals exacerbates the knock-on effects[12], as well as delaying progress towards SDG 1 that had been going well prior to the pandemic[35]. The next most impacted is the goal of industry, innovation and infrastructure (SDG 9), followed by sustainable cities and communities (SDG 11), quality education (SDG 4), strong institutions (SDG 16), good health and well-being (SDG 3), and affordable and clean energy (SDG 7). Noticeably, the impacts on SDGs 4, 7, 9 and 11 are high, in contrast with the view that the impacts on them would be mixed or moderate[35].

The results highlight that the cascading effects amplify the shock loss at the global scale, as the indirect shock loss is almost eight times greater than the direct shock loss. The goal that experienced the highest indirect impacts is SDG 1, followed by SDGs 4, 3, 7 and 11, which are highly interconnected with other goals. The results also reveal that SDG 9 incurred the most growth delay loss. This finding implies that reduced resources and investment for the sake of overcoming COVID-19 impacts may have taken a considerable toll, especially for SDGs that were progressing rapidly before the pandemic[35]. It may be caused by the fact that they require a large commitment to maintain the trend or lose momentum. This also happened to some extent to SDGs 1, 8, and 2. Therefore, redirecting resources and investment back to the implementation of those SDGs is essential if better recovery is desired in order to meet the goals by 2030.

Overall, the results highlight considerable hidden impacts on the development of the SDGs beyond the apparent effects. This suggests that the COVID-19 impacts on global progress towards the SDGs can be significantly underestimated if the growth delay loss and indirect shock loss induced by the cascading effects are ignored.

However, the results also show that the cascading effect could also have indirect benefits for the SDGs, such as responsible consumption and production (SDG 12), climate change (SDG 13), and life below water (SDG 14). Considering that the
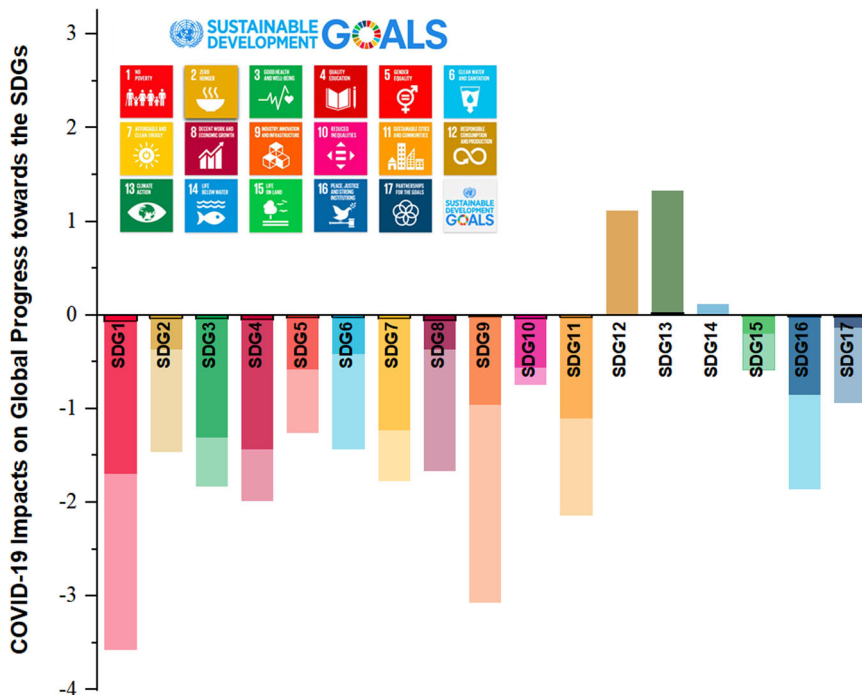
Fig. 4 The degree of COVID-19 impacts on global progress towards the SDGs. The value of COVID-19 impacts is the sum of the direct (darkest color) and indirect (lighter color) shock loss and growth delay loss (lightest color). A positive value indicates positive effects on the SDGs, while a negative value indicates negative effects. The value used to quantify the global impacts on the SDGs represents the relative degree, and it is determined by a change in the SDG index (a score representing the performance towards achieving each SDG) by 2030 after COVID-19 (see details in Methods). The logos of the SDGs are sourced from www.un.org/en/sustainable-development-goals.

beneficial effects of COVID-19 impacts on SDGs 12, 13 and 14 were relinquished during recovery[9,10,33,34], they are not considered in the analysis of growth delay loss.

COVID-19 impacts on regional progress towards the SDGs by 2030. We represent the change due to COVID-19 shocks as the indicative progress loss (i.e., the proportion of the total progress loss to what would have been achieved by 2030) and spatially map the change in SDG progress by region. We then categorize them as impacts of COVID-19 at five levels, as shown in Fig. 5 (more information is provided in Methods). We find that regions with overall impacts above the medium level include Latin America and the Caribbean, Sub-Saharan Africa, South Asia, the Middle East and North Africa. It is primarily due to that there are most countries in these regions that have less coping capacity, and are more vulnerable to the impacts of COVID-19[36]. The impacts in these regions are in the range of 1.5 to 1.9 times those in East Asia and the Pacific, which are the least affected[34,35,37]. Approximately 81% of countries in Sub-Saharan Africa incurred impacts above the medium level. Countries highly impacted in other regions include Colombia, Georgia, Montenegro, Bosnia and Herzegovina. In fact, there is no country in which progress towards the SDGs was immune to COVID-19 impacts. It is envisaged that that progress towards the SDGs in 62% of countries would experience medium to high impacts of the pandemic.

More specifically, progress towards SDG 9 (industry, innovation and infrastructure) was mostly impacted, and it received almost twice the average impacts of COVID-19 on all other SDGs, followed by SDGs 11, 16 and 3. This is even more evident in the regions of Sub-Saharan Africa, South Asia, and Latin America and the Caribbean. This is because SDG 9 was underperforming in these regions even before COVID-19, such as the low population using the Internet (SDG 9.1) and low R&D expenditures (SDG 9.6).The decline in industrial output, as well

as bankruptcy and closure of some industries due to the pandemic may further exacerbated the situation[35]. In addition, it is worth noting that progress towards SDG 1 in Sub-Saharan Africa and towards SDGs 3, 10, 11, and 16 in Latin America and the Caribbean were also highly impacted. Compared to other regions, progress towards those goals in approximately 79% of Latin America and Caribbean countries was impacted at a level no less than moderate.

Additionally, the findings show that, in comparison to the total consequences, the average direct effects of the COVID-19 pandemic on progress toward the SDGs for all areas were relatively low (see Fig. 5). However, for all regions, the average indirect impacts were more than twenty times greater than the average direct impacts. Latin America and the Caribbean experienced higher average indirect effects than other regions. They were subject to an average indirect effect approximately three times higher than one in East Asia and the Pacific, which was the least affected region. One reason is that, for Latin America and the Caribbean, the main positive correlation between SDGs in most countries greatly exacerbates the chain reaction of negative effects of the pandemic[12]. The indirect impacts of COVID-19 on progress towards SDGs 1, 3, 4, 7, 9 and 11 in Latin American and Caribbean countries and North America were at least moderate. Especially for SDG 1, as well as for Europe and Central Asia and the Middle East and North Africa, the degree of indirect impacts was demonstrated to be least moderate. In addition, Europe and Central Asia experienced at least moderate indirect effects on SDGs 3 and 4.

COVID-19 impacts on national progress and risks of countries to achieve the SDGs by 2030 after COVID-19. Among the income groups, for countries with income levels from high to low, COVID-19 generally had increasing impacts on the progress towards the SDGs by 2030 (see Supplementary Fig. 4 and more
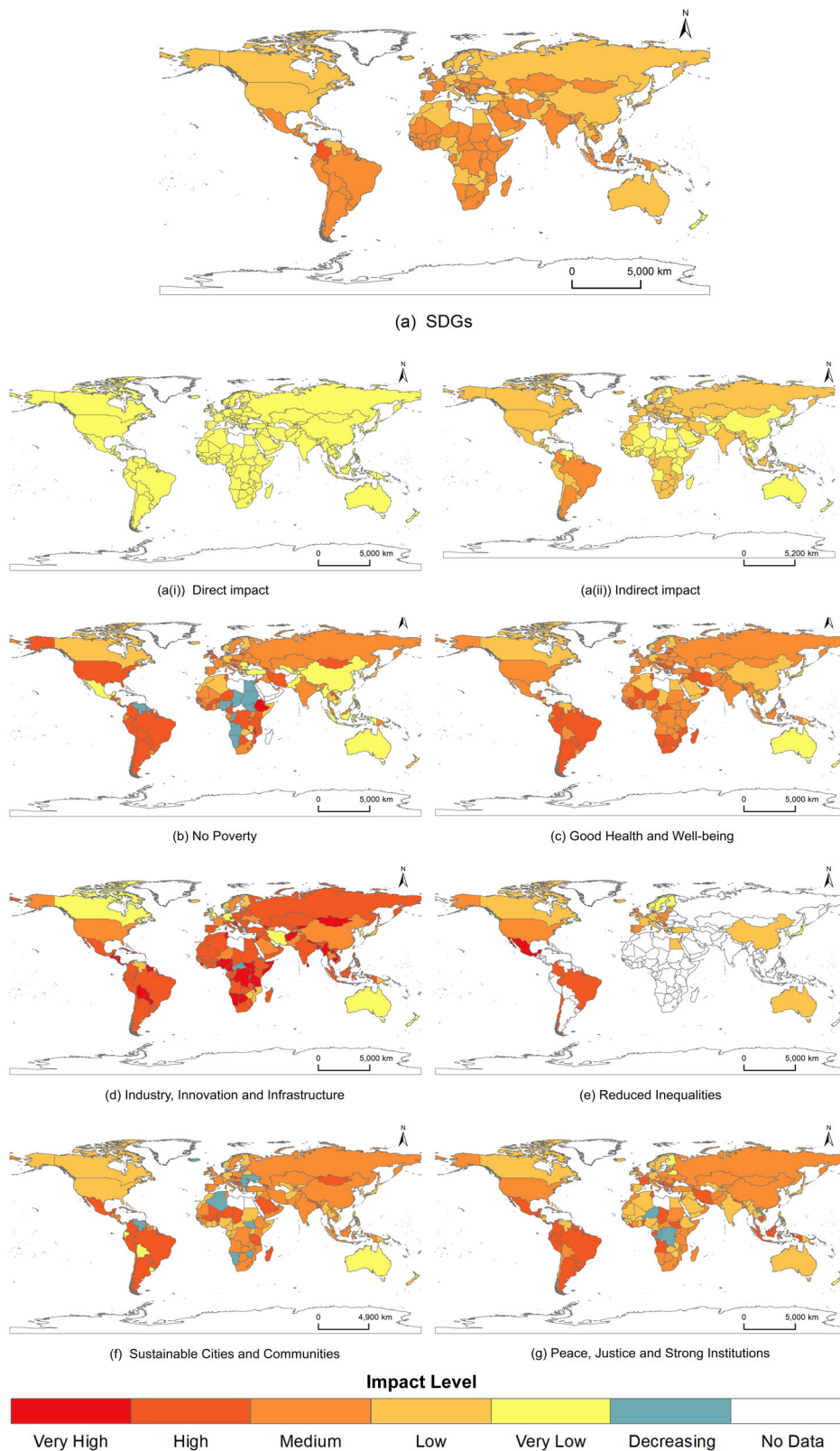
Fig. 5 COVID-19 impacts on regional progress towards the SDGs. a The average impact of COVID-19 on regional progress towards the SDGs. **a**(i) and (ii) respectively present the average direct and indirect impact of the COVID-19 on progress towards the SDGs for each region. For each SDG, the individual indirect effects for each region are presented in Supplementary Fig. 3. The impacts of COVID-19 on regional progress towards SDGs 1 (**b**), 3 (**c**), 9 (**d**), 10 (**e**), 11 (**f**), and 16 (**g**). The impacts on progress towards SDGs 1, 3, 9, 10, 11, and 16 are highlighted due to the significance of the effect in regions. The regional impacts of COVID-19 on other SDGs are depicted in Supplementary Fig. 2. Details about the impact levels are shown in Supplementary Table 3. The category "decreasing" indicates that the country was moving backwards even before COVID-19, suggesting enormous challenges for it in meeting SDGs with substantial uncertainties.

details in Methods). LICs (low-income countries) were the most affected, with average impacts that were around 1.4 times greater than those in high-income countries. About 84% of LICs were affected above the medium level, i.e. Afghanistan, Bangladesh, and Nepal. However, SDG 17 in HICs (high-income countries) was affected by COVID-19 almost 1.4 times more than in LICs. Notably, COVID-19 had moderate or greater effects on SDGs 3 and 9 for all four income categories. Besides, SDG 7 and 11 in poorer countries (i.e. low and lower-middle-income countries) and SDG16 in richer countries (i.e. high and upper-middle-income countries) both suffered medium and above impacts by COVID-19. Additionally, the results demonstrate that the average direct effects of the COVID-19 pandemic on progress toward the SDGs for all income levels were rather small. The average indirect effects, however, were more than twenty-four times bigger than the average direct effects across all income levels. Furthermore, the indirect impacts of COVID-19 on HIC's progress towards SDG 1 and 3 were no less than moderate.

For a country, the risk of failing to achieve the SDGs by 2030 after COVID-19 is considered to be dependent on the expected progress gap in meeting the SDGs by 2030 prior to COVID-19 as well as the indicative progress loss, as previously described. To measure the relative loss of SDG progress among countries, we normalize the indicative progress loss by applying the standard score (see more details in Methods). The risk is then categorized into high/medium/low on the basis of the expected progress gap prior to COVID-19 and the standard score of the post-COVID-19 indicative loss, as shown in Fig. 6.

Distinctly, the post-COVID-19 risks of national progress towards the SDGs differ by the four income groups. Notably, for countries with income levels from high to low, there are an increasing number of SDGs that could not be achieved with the increasing expected pre-COVID-19 gap by 2030. The same trend, as shown by the number of SDGs with a standard score above zero, manifests again in the progress towards the SDGs experiencing even more setbacks in poorer countries (i.e., low-income countries (LICs) and lower-middle-income countries (LMICs)) than in richer countries (i.e., high-income countries (HICs) and upper-middle-income countries (UMICs)) in the post-COVID-19 period.

Overall, as displayed by the dotted envelops in Fig. 6, HICs (e.g., New Zealand and Australia) had made good progress towards achieving the SDGs before COVID-19 and were little affected by the pandemic, thus demonstrate that they would have low risks in achieving the SDGs by 2030. In comparison, the progress made in UMICs (e.g., Thailand and China) before the pandemic was not balanced but was relatively less affected by the pandemic. In LMICs (e.g., Georgia and Moldova), the impacts of the pandemic started to take effect on top of unbalanced progress before the pandemic. LICs (e.g., Ethiopia and Burkina Faso) were mostly disadvantaged by both large gaps in progress before the pandemic and considerable impacts afterwards. This is mainly because poor countries lack public spending and access to capital markets to recover quickly and move the SDG progress forward[34,35,38].

More specifically, the risk in HICs is low for most of the SDGs. Only SDG 10 (reduced inequalities) falls to a medium level, which was indeed a concern even before the pandemic[35,39,40]. Affected slightly more than the average by COVID-19 are SDG 1 (no poverty), SDG 3 (good health and well-being), and SDG 9 (industry, innovation and infrastructure), but their well-advanced status (or smaller gap) prior to COVID-19 ensures that they maintain their low-risk status.

In UMICs, SDG 10 stands out in the category of high risk, which was already causing concern before COVID-19[35,39,40]. However, the impact of COVID-19 on SDG 10 is below the

average, implying that it is more an ongoing issue than a ramification of COVID-19. The situation is similar for SDG 15 (life on land) and SDG 17 (partnerships for the goals), which are at a medium risk level. In addition, SDGs 9 (industry innovation and infrastructure) and 16 (peace, justice and strong institutions) experience medium risk and are more affected by COVID-19.

LMICs had generally made good progress towards SDGs 1 (eradicate poverty), 4 (quality education) and 8 (decent work and economic growth) before the pandemic, and their progress has been less affected by COVID-19. However, most SDGs in those countries are expected to experience risks ranging from medium to high levels owing to a lack of progress even before the pandemic, especially for SDG 5 (gender equality). In addition, progress towards SDG 9 suffers from both a lack of progress before COVID-19 and considerable impacts of the pandemic, leading to high risk.

It is important to note that progress towards the SDGs in LICs generally encountered major lags even before COVID-19, and the lags have been exacerbated by the impacts of COVID-19. This has caused the risks to range from middle to high levels. It is a particular concern that there is a high risk of failing to achieve SDG 9 (industry, innovation and infrastructure) and SDG 7 (affordable and clean energy), while the SDGs associated with people's basic needs, such as SDGs 1 and 3, also experience risks at the high end of the medium level.

Discussion

Our study provides new insights into impacts on global, regional and national progress towards the SDGs following the shocks of COVID-19, which include the increased mortality and morbidity caused by the pandemic outbreak, economies and activities slowed by lockdowns, and depleted public resources. The impacts innovatively capture both direct and indirect effects as well as immediate setback and deceleration in progress towards achieving the SDGs by 2030.

The impacts on global progress towards the 17 SDGs as a result of COVID-19 are mostly consistent with the results of other studies that found that SDG 1 was the most affected[9,35]. More important, our study further manifests the significance of growth delay loss and indirect or cascading shock loss due to interlinkages among the SDGs. Noticeably, the impacts on SDG 9 became more prominent due to its having the highest growth delay loss. It implies that the SDGs that were rapidly progressing before the pandemic can be considerably impacted during the recovery, as the resources and investment critical to maintaining their momentum were redirected to overcome the pandemic. Consequently, more efforts or investment will be required to rebuild them.

The findings indicate that the progress toward achieving the SDGs is greatly hampered by the indirect effects of the COVID-19 pandemic. The results highlight SDGs 3 and 16 are key goals that have strong interlinkages with many other goals, and changes in them can magnify the overall impact by cascading effects on other goals, as shown in Fig. 3. A general risk management approach to mitigating the global impacts of COVID-19 is to directly reduce the shocks by improving public health measures. In combination with more measured lockdowns and effective public resource use, it can reduce the mortality and morbidity. Having said that, more targeted measures to reduce the immediate direct impacts of COVID-19 on SDGs 3 and 16 could considerably alleviate the indirect impacts. Additionally, the focus on peace, justice and strong institutions in SDG 16 can also broadly benefit the implementation of all other SDGs when facing COVID-19 shocks.
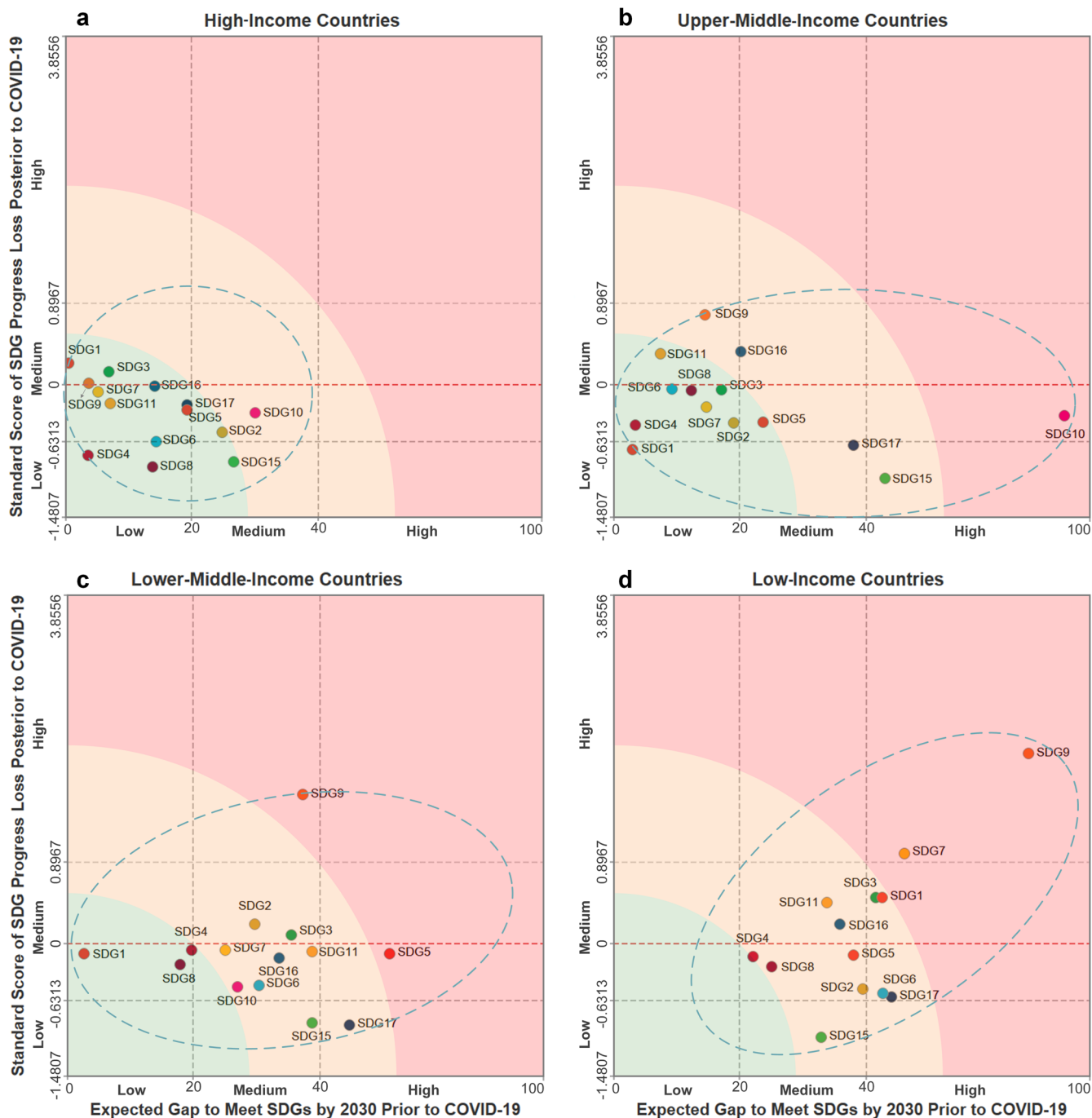
Fig. 6 Post-COVID-19 risks to progress towards the SDGs in countries within four income groups: high, upper-middle, lower-middle, and low income.
The zero standard score represents the average relative change caused by COVID-19 impacts on each SDG across all countries. A score below zero implies an income group of countries with better progress than the average of all countries, and vice versa. The red, yellow and green colors represent three levels of risk, i.e., high, medium and low, respectively, where the low-risk area is bounded by the circle that passes the intersection point of the zero standard score (average impact) and the expected gap at 20 (low), the medium-risk area is bounded by the circle that passes the intersection of the upper ends of the medium standard score and medium expected gap, and the other is the high-risk area. The envelops are applied to schematically describe the clustering profiles of progress towards all SDGs. **a** High-income countries (HICs): the high degree of clustering in the low-risk area demonstrates their good progress towards the SDGs before COVID-19, while their high resilience also prevents them from considerable impact of the pandemic; **b** upper-middle-income countries (UMICs): the relative clustering around the zero standard score but spreading across the expected gap prior to COVID-19 illustrates unbalanced progress towards the SDGs before COVID-19 but is not considerably impacted by the pandemic; **c** lower-middle-income countries (LMICs): the cluster of SDGs starts to spreads as a result of effects created by both lack of progress prior to COVID-19 and its impacts, leading more falling in the middle- or high-risk categories; and **d** low-income countries (LICs): the cluster shows more towards the end of high expected gaps in achieving the SDGs prior to COVID-19 and shifts higher to represent more impacts from the pandemic. SDG 10 in LICs is not included in the calculation due to insufficient data.

The impacts also demonstrate regional differences. Countries in Latin America and the Caribbean, Sub-Saharan Africa, South Asia, the Middle East and North Africa were more severely affected. Therefore, to reduce COVID-19 impacts, there is a strong need to improve their resilience in general, such as health system capacity specific to COVID-19 and relevant institutional and infrastructure capacities[36]. It is particularly important to foster industry innovation and build resilient infrastructures in SDG 9, as the pandemic severely impacted development in the regions of Sub-Saharan Africa, South Asia, Latin America and the Caribbean. In addition, the goal for poverty reduction in SDG 1 was highly affected by COVID-19 in Sub-Saharan Africa, which is in alignment with the conclusions of other research[41]. There are more concern that the progress towards SDG 1 in the region had fallen behind prior to the pandemic (see Supplementary Fig. 1). Therefore, more financial and technical support is urgently required to enhance the chance of the region to meet the goal of poverty reduction by 2030. In comparison, the region of Latin America and the Caribbean received the most impacts on its progress towards fostering industry, innovation and infrastructure in SDG 9; ensuring healthy lives and well-being in SDG 3; reducing inequality in SDG 10; promoting sustainable cities and communities in SDG 11; and strengthening peace, justice and strong institutions in SDG 16. Therefore, the corresponding investment in those SDGs should be made to ameliorate the impact of COVID-19. It is interesting that progress towards the SDGs in the region of East Asia and the Pacific was least affected because the countries in the region effectively responded to the pandemic outbreak, as illustrated in a previous study[34,35,37]. Their success depended significantly on excellent hygiene practices among the public and receiving intensive public health care, from which other countries can learn[35].

These results also highlight the discrepancies between nations with different incomes. The greater impacts in poorer countries is resulted by the lack of financing and other measures to curb the pandemic[35]. The COVID-19 crisis has further put pressure on donor aid budgets (SDG 17), reinforcing the need to increase fiscal space in the poorest countries through more instruments (including taxes, ODA, other additional resources, and debt relief) to achieve SDG[34,42]. The observed high impacts on SDG 3 across all different income categories were broadly consistent with the findings that all nations are required to "strengthen their capacity for early warning, risk reduction and management of national and global health risks". Even for the high-income countries, similar actions are also necessary despite that they were considered to be best prepared to face pandemics[35]. In poor countries, the pandemic severely hampers SDG 7 because disruptions in the supply chain can wreak havoc on energy services (e.g., SDG 7.1 electricity and SDG 7.2 clean energy), and reduced incomes can limit people's ability to pay for energy services[42]. Yet access to energy is a prerequisite for economic prosperity health and education, and an important multiplier for all SDGs. Without these fundamentals, the most vulnerable are at risk of being trapped in a cycle of poverty and inequality, so the primary goal is to increase access to energy for those who fall last[43]. SDG 16 (Peace, Justice and Strong Institutions) in poorer counties has stagnating even before COVID-19. In richer countries, its progress was improved before but has since been delayed and undermined by COVID-19. as a result of extraordinary measures introduced by some governments to increase their power, leaving citizens with relatively high levels of perceived corruption (SDG16.6), low freedom of expression (SDG 16.9), or high levels of insecurity (SDG 16.3)[35].

We have demonstrated the risks of national progress towards the SDGs after COVID-19 on the basis of income groups. In HICs and UMICs, there are relatively more risks of failing to achieve SDG 10 by 2030, but the risks are related to ongoing development gaps in reducing inequality before the pandemic. It is associated to some extent with the phenomenon of "poor government but rich private sector", which reduces the capacity of government to redistribute wealth to reduce inequality, especially for disadvantaged groups[40]. This is more evident in UMICs, which have even less wealth and subsequent capacity to address the issue. Government capacity could be enhanced by increasing revenue or restructuring spending so that policies such as expanding social safety nets to reduce inequality could be developed[44]. However, this could be politically challenging.

Additionally, UMICs have faced "major challenges" in progressing towards SDGs 9, 15, 16, and 17. Among them, SDGs 9 and 16 experienced setbacks due to COVID-19 impacts, while SDGs 15 and 17 were hampered by pre-COVID-19 development gaps. Therefore, UMICs need more targeted options to address both existing concerns and the effects of COVID-19 in association with different SDGs. For example, any unsustainable supply chain could be limited to reduce the loss of terrestrial biodiversity and deforestation in SDG 15[35], and partnerships among government and private sectors in SDG 17 could be strengthened to broadly address the development of the SDGs[38]. For impacts of COVID-19, especially in regard to the increased authoritarianism in response to COVID-19, governance to strengthen rather than reduce freedom of expression and enhance the transparency of governmental responses to the pandemic are important in continuing to advance SDG 16. In addition, inequalities in UMICs can be affected primarily by unequal economic growth[45], which became even more notable during the pandemic as a result of substantial income loss in disadvantaged groups. Moreover, disparity in the possibility of education leads to disadvantaged groups having fewer options, not only to find income sources[45] but also to endure the impacts and, more importantly, recover from the impacts of the pandemic. Therefore, policies designed to reduce inequality in social security in terms of both income and education can be very important to moderate COVID-19 impacts on UMICs.

In poorer countries, the recovery of progress towards the SDGs after COVID-19 continues to be hampered by problems that occurred widely across SDGs even before the pandemic, as shown in our results. The International Monetary Fund (IMF) pointed out that poorer countries account for only approximately 15% of global investment, even though they make up half of the world's population[46]. This is demonstrated by a lack of public expenditures and market access to capital[34,35,38], which makes the recovery of progress towards the SDGs after the COVID-19 impacts even more challenging in LMICs and LICs. Therefore, a strong call to act by providing broader aid to LICs and LMICs is needed to address these fundamental issues. The call to improve industry innovation and infrastructure is even more compelling, as our results reveal that SDG 9 has been considerably impacted in addition to the development gap that existed before the pandemic. The UN pointed out that small-scale industries that are common in developing countries were severely affected by the pandemic owing to a lack of capital and investment. The situation is even more dire in the poorest countries[42]. In addition to relevant policies, taking advantage of the latest technological developments to advance industry innovation can be effective, such as universal digital services that can offer wide-open markets and affordable e-services, e.g., e-education, telemedicine and e-financing[44].

In LICs, our results show that progress towards SDG 7 is at high risk after COVID-19. In fact, the UN noted that COVID-19 could impede progress towards SDG 7 in LICs, although great progress towards accessing clean fuels and technologies was made prior to the outbreak[47]. This was again caused by increasing

expenditures in response to COVID-19, using funds that could otherwise have been invested in SDG 7. Progress towards SDGs 1 and 3 was also largely impacted by COVID-19 in LICs, as shown by income losses from reduced tourism, remittances, and exports of goods[35]. Additionally, the longtime poor public health systems further exacerbated COVID-19 impacts. Efforts to eradicate poverty and improve health and well-being must be further pursued.

Although this study provides important and interesting findings, it has to be pointed out that there are some limitations in data and methodology. First, the identified COVID-19 impacts on progress towards SDGs were based on the data from 91 indicators, rather than all 231 United Nations' indicators, primarily because most of the other indicators are either hard to quantify or lack data[34]. As more data become available in the future, our approach can be applied to the updated SDG indicators database to provide a more comprehensive and detailed picture. Second, countries may use the lessons learned from COVID-19 to make rapid progress toward achieving the SDGs, such as increasing global cooperation, promoting technology development, accelerating digitization, and raising health awareness[48]. Future research can further investigate the other paths with rapid recovery based on lessons from COVID-19.

In conclusion, the overall impact of COVID-19 on the progress towards the SDGs has multiple facets. It is not only affected by the interwoven relationships among SDGs that magnify the impact, but also depending on the status of each country in terms of its latest SDG progress performance and resilience in recovering from COVID-19. We thus propose a relatively simple and reasonable approach to analyze the impacts of COVID-19 on progress towards the SDGs by 2030 at the global, regional and national scales. It will help to prioritize actions and take more effective approaches to recover and rebuild progress towards the SDGs in the post-COVID-19 period.

Methods

The logic of this study is illustrated in Fig. 7. We develop a process-based scenario to systematically assess COVID-19 impacts at global, regional and national scales. COVID-19 impacts were simulated based on the approach, as shown in Fig. 1, covering the entire process of the SDGs in response to the COVID-19 shocks. The approach includes the shock loss related to the immediate response of SDG progress to the COVID shocks and growth delay loss in association with the deceleration and recovery of SDG progress following the immediate response. Importantly, it depends on countries, affected not only by their capacity to prevent or reduce shock loss but also by their ability to recover, as emphasized by the United Nations[43].

The first step was to evaluate the global COVID-19 impacts represented by the shock loss and growth delay loss of SDG progress in each country following three COVID-19 shocks (i.e., increased mortality and morbidity associated with the pandemic outbreak, economies and activities slowed by lockdowns and depleted public resources). The second step was to measure the COVID-19 impacts on regional and national progress towards the SDGs by 2030 in the post-COVID period. The third step was to categorize the risks of countries in different income groups failing to achieve the SDGs by 2030.

COVID-19 impacts on global progress towards the SDGs by 2030.

COVID-19 impacts on progress ($T_{c,g}$) for each goal (g) in each country (c) include shock loss ($S_{c,g}$) and growth delay loss ($G_{c,g}$), the calculation formula is as follows:

$$T_{c,g} = S_{c,g} + G_{c,g} \tag{1}$$

The shock loss, or the loss with respect to setbacks in progress towards the SDGs induced by COVID-19 shocks, was estimated in three steps. First, the nominal direct impacts of COVID-19 were mapped on the 92 SDG indicators through ten paths of impacts pertinent to the three COVID-19 shocks based on comprehensive analysis of the literature (see Supplementary Note 1). Second, the nominal indirect impacts between indicators of the SDG targets were calculated. Third, the nominal direct and indirect impacts were then adjusted by COVID-19 severity and the degree of each country's progress towards the SDGs before the pandemic to finally attain the shock loss of SDG progress in each country. Fourth, the growth delay loss was simulated by assuming that progress towards each SDG initially decelerated after the shock loss and then recovered, leading to a delay in progress towards the SDGs. The COVID-19 impacts on the SDGs in each country

were combined effects of shock loss and growth delay loss. COVID-19 impacts on SDG progress in 163 countries were eventually evaluated (see Supplementary Table 2 for the specific countries). The impacts on global progress towards the SDGs were estimated by the population-weighted aggregation of the COVID-19 impacts on all countries.

First, the nominal direct impacts of COVID-19 on SDGs were estimated. We obtained the performance of progress towards all SDGs in each country from the Sustainable Development Report (SDR), which has been jointly issued by the Sustainable Development Solutions Network (SDSN) and the Bertelsmann Foundation every year since 2016[34,49]. SDR 2021 was chosen as our dataset because it has the most countries and indicators. A total of 92 indicators in 193 countries were selected from the report, with the same set of indicators being utilized for all countries to have comparable scores (see indicators in the Supplementary Data 1 for details). International organizations provide the majority of the data utilized in this report, such as the World Bank, the World Health Organization, the Food and Agriculture Organization, the United Nations Children's Fund and others, which have comprehensive and stringent data-validation processes[34].

On the basis of SDR 2020[35] and SDR 2021[34], together with the relevant literature (see details in Supplementary Note 1), the nominal direct impact of COVID-19 on each SDG indicator can be affected through ten paths aligned with three initial COVID-19 shocks. The degrees of nominal direct impacts are then divided into six levels (see the scoring criteria in Supplementary Table 1). The detailed justification in association with the specific impact paths of COVID-19 on the specific SDG indicators can be found in Supplementary Note 1. The impact pathway and score for each of the 92 SDG indicators are shown in Supplementary Data 1. To better demonstrate, the direct consequences of COVID-19 shocks acting on specific SDG indicators through impact pathways are shown graphically in Fig. 2. In the specific calculation process, the calculation formula is as follows:

$$A = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ \vdots \\ a_i \\ \vdots \\ a_{92} \end{bmatrix} D_G = \begin{bmatrix} D_1 \\ D_2 \\ D_3 \\ \vdots \\ D_g \\ \vdots \\ D_{17} \end{bmatrix} \tag{2}$$

Where A is the nominal direct impact matrix of COVID-19 on 92 indicators through specific impact paths, and a_i is the nominal direct impact score of COVID-19 on the ith indicator. D_G is the nominal direct impact value of COVID-19 on 17 SDGs, D_g represents the nominal direct impact value of COVID-19 on a certain SDG. $D_g = \frac{\sum_{j=1}^{n_g} a_{gj}}{n_g}$ (g = 1, 2, 3......17), n_g represents the number of indicators under the gth SDG, and a_{gj} is the nominal direct impact value of COVID-19 on the jth indicator under the gth SDG.

By referring to the "short-term impacts of COVID-19" in SDR 2020, on which the scoring is based, as described above, we also categorized the results of the nominal direct impacts of COVID-19 shocks on 17 SDGs into three levels for visualization, i.e., highly negative impact, mixed or moderately negative impact, and impact still unclear (see Fig. 2).

Second, the nominal indirect impacts of COVID-19 on SDGs were estimated. Following Pradhan[12], Kroll[13] et al., we used Spearman correlation coefficients to represent the interconnections between two indicators of the SDGs. We analyzed the interconnections between SDG indicators to assess the cascading effects of COVID-19 on the SDGs. We applied the data in association with the same 92 indicators of 17 SDGs previously analyzed from 2010 to 2019 for all 193 UN member states (excluding data for 2020 and 2021, which may have been affected by COVID-19; as of October 1, 2021; raw data are available at www.sdgindex.org). We finally examined the interconnections of a total of 3933 indicator pairs for 10 consecutive years, as 253 were missing among 4186 pairs of indicators due to unavailable data. To avoid false correlation if the indicator definition was in opposition to the intended trajectory, the time series were multiplied by −1 and, if they were concurrent, by 1 (see detailed signs in Supplementary Data 1). The correlation between indicators was considered statistically significant with a p value of less than 0.05. In the calculation process, the calculation formula is as follows:

$$B = \begin{bmatrix} b_{1,1} & b_{1,2} & \cdots & b_{1,92} \\ b_{2,1} & b_{2,2} & \cdots & b_{2,92} \\ \vdots & \vdots & b_{i,i'} & \vdots \\ b_{92,1} & b_{92,2} & \cdots & b_{92,92} \end{bmatrix} \tag{3}$$
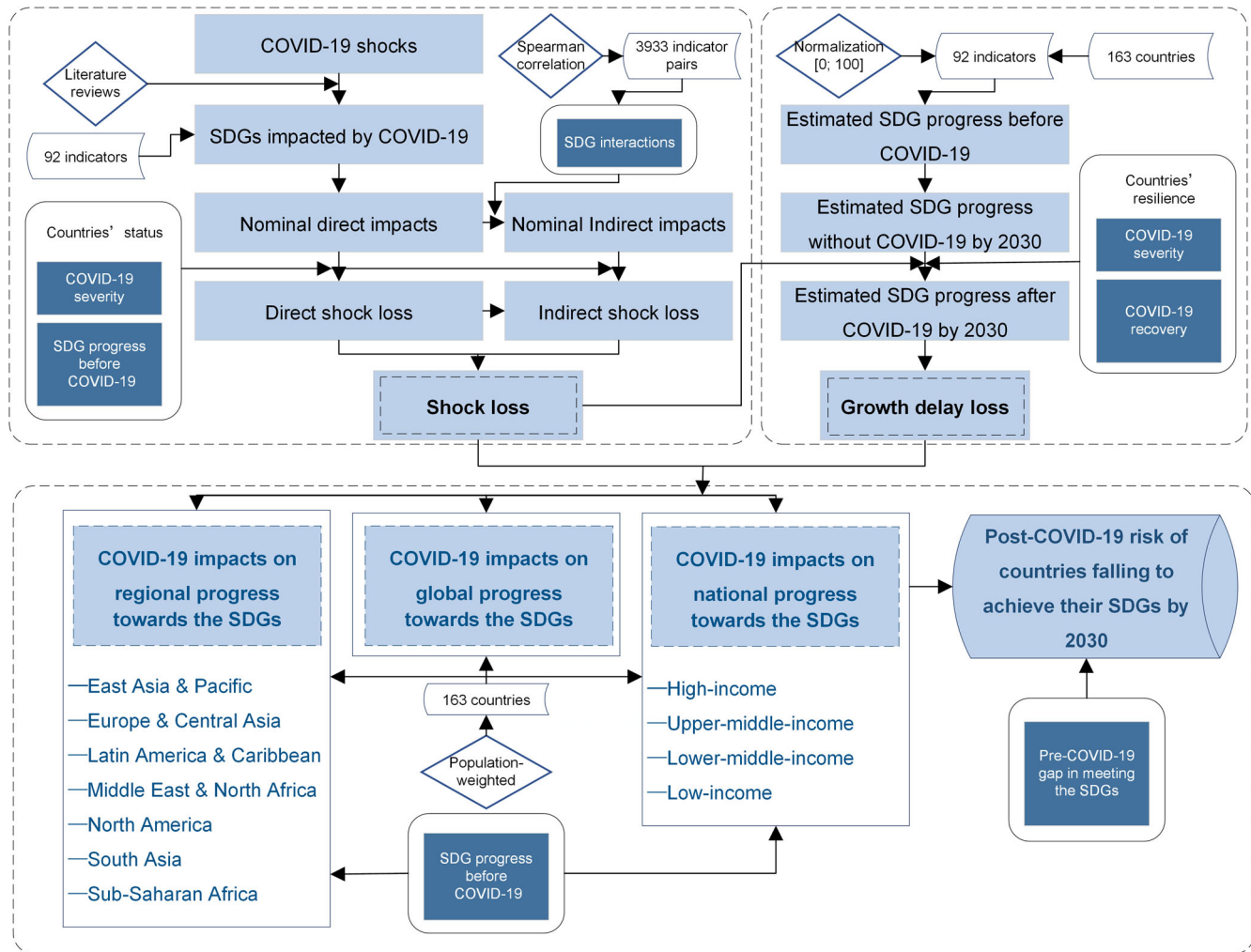
Fig. 7 Approaches in the assessment of COVID-19 impacts on global progress towards SDGs by 2030. This study considers the impact of COVID-19 pandemic on SDG progress as a combined effect of shock loss and growth delay loss.

$$I_G = AB = \begin{bmatrix} a_1 b_{1,1} + a_2 b_{1,2} + \cdots + a_{92} b_{1,92} \\ a_1 b_{2,1} + a_2 b_{2,2} + \cdots + a_{92} b_{2,92} \\ \vdots \\ a_i b_{i,i'} \\ \vdots \\ a_1 b_{92,1} + a_2 b_{92,2} + \cdots + a_{92} b_{92,92} \end{bmatrix}$$

$$= \begin{bmatrix} I_{1,1} + I_{1,2} + \cdots + I_{1,17} \\ I_{2,1} + I_{2,2} + \cdots + I_{2,17} \\ \vdots \\ I_{g,g'} \\ \vdots \\ I_{17,1} + I_{17,2} + \cdots + I_{17,17} \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_g \\ \vdots \\ I_{17} \end{bmatrix} \quad (4)$$

Where, matrix B is the correlation matrix among indicators pairs with impact relation, and $b_{i,i'}$ is the impact coefficient of i'th indicator on the ith indicator. I_G is the nominal indirect impact value of COVID-19 on 17 SDGs. $a_i b_{i,i'}$ is the nominal indirect impact value of i'th indicator on the ith indicator. $I_{g,g'}$ represents the nominal indirect impact value of the g'th goal on the gth goal, the nominal indirect impact values among the 17 SDGs induced by the cascading effects of COVID-19 through their interconnections are represented graphically as Fig. 3, $I_{g,g'} = \frac{\sum_{j=1}^{n_g} \sum_{j'=1}^{n_{g'}} a_{gj} b_{gj,g'j'}}{n_g}$ (g and g' = 1, 2, 3……17), n_g represents the number of indicators under the gth goal, $n_{g'}$ represents the number of indicators under the g'th goal, $b_{gj,g'}$

j' is the impact coefficient of j'th indicator under the g'th on the jth indicator under the gth SDG, $a_{gj} b_{gj,g'j'}$ is the nominal indirect impact value of COVID-19 of j'th indicator under the g'th on the jth indicator under the gth SDG. I_g is the nominal indirect impact value of COVID-19 on the gth goal.

Third, the shock loss of SDG progress in countries were estimated. We obtained the shock loss ($S_{c,g}$) for each goal (g) in each country (c) by combining the direct shock loss ($D_{c,g}$) and indirect shock loss ($I_{c,g}$) as follows:

$$S_{c,g} = D_{c,g} + I_{c,g} \quad (5)$$

$$D_{c,g} = \frac{D_g \times S_c \times X_{c,t}}{1000} \quad (6)$$

$$I_{c,g} = \frac{I_g \times S_c \times X_{c,t}}{1000} \quad (7)$$

Where D_g is the nominal direct impact on each SDG (g = 1, 2, 3……17) and I_g is the indirect nominal impact on each goal (g = 1, 2, 3……17). S_c, the GCI Severity Index, is the extent to which the c-th country is affectd by the COVID-19 shocks. $X_{c,t}$ represents the SDG index of each country in the most recent year before the pandemic (i.e., 2019), describing the overall progress performance of 17 SDGs from 0 (worst) to 100 (best). One-thousandth is the adjustment factor, as we assume that the impact on the SDGs was within the range of the world GDP growth rate of −3.1% in 2020 in the World Economic Look by the IMF[50].

The GCI Severity Index among the Global COVID-19 Index (GCI) was developed by Malaysia's Performance Management & Delivery Unit (PEMANDU Associates) in collaboration with the Malaysian Ministry of Science, Technology, and Innovation (MOSTI) and recognized by the World Health Organization (WHO)[31]. We applied the latest adjusted SDG indicator data included in SDR 2021 for retrospective calculations to calculate the SDG progress of each country in 2019. In more detail, we calculated the SDG index in three steps. (1) Establish

performance thresholds (upper and lower bounds) for each indicator. Any greater than or equal to the upper limit of the indicators has a score of 100 (i.e., best performance), while any less than or equal to the lower limit of the indicators has a score of zero (i.e., worst performance). (2) Normalize the data to the range of [0; 100] to facilitate the interpretation and comparison of all indicators. (3) Aggregate indicators of the same SDG by using the arithmetic mean in an equal weight, as described by the SDR (available at www.sdgindex.org). A similar approach was used by Schmidt-Traub[51], Xu[52] et al. to assess the process of sustainable development.

Fourth, the growth delay loss of SDG progress in countries were estimated. Consistent with the SDR[34,35,38,39], we represent the progress rate towards goal "g" before COVID-19 by its average annual rate, $Rate_{pre,c,g}$. Based on the development trend of the SDGs, typically in the most recent period of 2015–2019:

$$Rate_{pre,c,g} = \frac{X_{c,g}(t_1) - X_{c,g}(t_0)}{t_1 - t_0} \qquad (8)$$

where $X_{c,g}(t)$ is the SDG index in year t for goal "g" in country "c", t_0 is typically in 2015, and t_1 is the end of the record period. The progress rates of the SDGs after the shock loss, $Rate_{post,c,g}(t)$, were assumed to slow down during the shock and then recover, as described by:

$$Rate_{post,c,g}(t) = \frac{1}{1 + \alpha e^{-\frac{t-2020}{\tau_{recover}}}} Rate_{pre,c,g} \qquad (9)$$

Where α represents the ratio of SDG growth rate deduction by the COVID-19 impacts, equaling the GCI Severity Index as a percentage. $\tau_{recover}$ is a time factor that reflects the speed of recovery of SDG growth, calculated using 1-the GCI Recovery Index (as a percentage). The GCI Severity and Recovery Index were both derived from the Global COVID-19 Index (GCI). It is expected to take 2–3 years for most countries to return to prepandemic levels. This estimate is consistent with the timing of the recovery in economic growth projected in the UN's Sustainable Development Goals Report 2021[42]. Thus, the expected progress towards the SDGs by 2030 is (see more details in Supplementary Fig. 1):

$$X_{post,c,g}(2030) = X_{c,g}(t_1) - S_{c,g} + Rate_{pre,c,g} \int_{t'}^{2030} \frac{1}{1 + \alpha e^{-\frac{t-2020}{\tau_{recover}}}} d\tau \qquad (10)$$

Where t' is the year to start recovery and 2020 was chosen because the world economy has been recovering since mid-2020 and is driven by large fiscal policies, as explained by the IMF[50]. The model takes into account the national capacities that are critical to developing resistance to COVID-19 shocks and speedy recovery after shocks based on national progress towards the SDGs by 2030. The capacity related to resistance is reflected by factors including confirmed cases per population relevant to COVID-19 and the Global Health Security Index[31]. Additionally, the capacity pertinent to recovery is described by factors including active cases, governance, and WHO universal health coverage[31]. Therefore, the growth delay loss by 2030 for goal g of country c was estimated by $G_{c,g}$:

$$G_{c,g} = X_{pre,c,g}(2030) - X_{post,c,g}(2030) - S_{c,g} \qquad (11)$$

Where $X_{pre,c,g}(2030)$ is the SDG progress expected to be achieved by 2030 prior to COVID-19 (see more details in Supplementary Fig. 1) and is given by:

$$X_{pre,c,g}(2030) = X_{c,g}(t_1) + (2030 - t_1)Rate_{pre,c,g} \qquad (12)$$

COVID-19 impacts on regional and national progress towards the SDGs by 2030. To highlight changes in SDG progress as a result of COVID-19 impacts, we applied the change ratio $T'_{c,g}$ to map the total impacts of COVID-19 on regional progress by 2030 (see Fig. 5):

$$T'_{c,g}(2030) = \frac{T_{c,g}}{X_{pre,c,g}} \qquad (13)$$

$$T'_{c,g,D}(2030) = \frac{D_{c,g}}{X_{pre,c,g}} \qquad (14)$$

$$T'_{c,g,I}(2030) = \frac{I_{c,g}}{X_{pre,c,g}} \qquad (15)$$

Where $T'_{c,g,D}(2030)$ and $T'_{c,g,I}(2030)$ is the direct and indirect impacts of COVID-19 on regional progress by 2030 for goal "g" in country "c", respectively. $T'_{c,g}(2030)$ was divided into five levels by using K-mean clustering (more details in Supplementary Table 3). For comparison with the total impact $T'_{c,g}(2030)$, the classification of $T'_{c,g,D}(2030)$ and $T'_{c,g,I}(2030)$ are consistent with the above five levels. The impacts of COVID-19 on progress in a region were based on the population-weighted average (Fig. 5). Furthermore, we used the same methodology as described above for regions to analyze the COVID-19 impacts on national progress towards the SDGs by 2030 in different income groups.

Post-COVID-19 risks of failing to achieve the SDGs by 2030. Finally, we assume that the risks of failing to achieve the SDGs by 2030 in each country in the post-COVID-19 period were decided by both the expected progress gap in meeting the SDGs by 2030 prior to COVID-19 and the indicative progress loss subsequent to COVID-19. We standardized the COVID-19 impacts on SDG progress in each country and then applied K-mean clustering to categorize the standard scores into high/medium/low levels for a clear comparison (see more details in Fig. 6). We also estimated the progress gap in meeting the SDGs by 2030 prior to COVID-19 with zero, implying that a country was almost certain to achieve a relevant goal. The expected gap ranges from 0 to 100, representing no gap to a full gap (no progress) in meeting each SDG by 2030. The progress gap in an income group was based on the population-weighted average and was also grouped into three levels: high, medium and low. The greater expected progress gap prior to COVID-19 and indicative progress loss subsequent to COVID-19 implies a higher risk of failing to achieve the SDGs by 2030. Combining the standard scores of SDG progress loss and progress gap, the post-COVID-19 risks to SDG progress were grouped into three levels: high, medium and low. The post-COVID-19 risks of national progress towards the SDGs are then summarized into four income groups defined by the World Bank to consider economic development: LICs, LMICs, UMICs, and HICs[32], where both the standard score and expected gap to represent an entire income group are weighted by the populations of the countries in the group.

References
1. Decade of Action to deliver the Global Goals (United Nations); https://www.un.org/sustainabledevelopment/decade-of-action/ (2019).
2. Editorial. Time to revise the sustainable development goals. *Nature* 583, 331–332 (2020).
3. Naidoo, R. & Fisher, B. Reset sustainable development goals for a pandemic world. *Nature* 583, 198–201 (2020).
4. Pradhan, P. et al. The COVID-19 pandemic not only poses challenges, but also opens opportunities for sustainable transformation. *Earths Future* 9, e2021EF001996 (2021).
5. Gao, L. & Bryan, B. A. Finding pathways to national-scale land-sector sustainability. *Nature* 544, 217–222 (2017).
6. Moallemi, E. A. et al. Early systems change necessary for catalyzing long-term sustainability in a post-2030 agenda. *One Earth* 5, 792–811 (2022).
7. Barbier, E. B. & Burgess, J. C. Sustainability and development after COVID-19. *World Dev.* 135, 105082 (2020).
8. Pradhan, P. A threefold approach to rescue the 2030 Agenda from failing. *Natl Sci. Rev.* nwad015 (2023).
9. 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).
10. Diffenbaugh, N. S. et al. The COVID-19 lockdowns: a window into the Earth System. *Nat. Rev. Earth Environ.* 1, 470–481 (2020).
11. Nilsson, M., Griggs, D. & Visbeck, M. Policy: map the interactions between Sustainable Development Goals. *Nature* 534, 320–322 (2016).
12. Pradhan, P., Costa, L., Rybski, D., Lucht, W. & Kropp, J. P. A Systematic Study of Sustainable Development Goal (SDG) interactions. *Earth's Future* 5, 1169–1179 (2017).
13. Kroll, C., Warchold, A. & Pradhan, P. Sustainable Development Goals (SDGs): are we successful in turning trade-offs into synergies? *Palgr. Commun.* 5, 140 (2019).
14. Lusseau, D. & Mancini, F. Income-based variation in Sustainable Development Goal interaction networks. *Nat. Sustain.* 2, 242–247 (2019).
15. Pedercini, M., Arquitt, S., Collste, D. & Herren, H. Harvesting synergy from sustainable development goal interactions. *Proc. Natl Acad. Sci. USA* 116, 23021–23028 (2019).
16. Ibn-Mohammed, T. et al. A critical analysis of the impacts of COVID-19 on the global economy and ecosystems and opportunities for circular economy strategies. *Resour. Conserv. Recycl.* 164, 105169 (2021).
17. Ahmed, F., Ahmed, N. E., Pissarides, C. & Stiglitz, J. Why inequality could spread COVID-19. *Lancet Child. Adolesc. Health* 5, e240 (2020).
18. Brulhart, M., Klotzbucher, V., Lalive, R. & Reich, S. K. Mental health concerns during the COVID-19 pandemic as revealed by helpline calls. *Nature* 600, 121–126 (2021).

19. Achdut, N. & Refaeli, T. Unemployment and psychological distress among young people during the COVID-19 pandemic: psychological resources and risk factors. *Int. J. Environ. Res. Public Health* **17**, 7163 (2020).

20. Gold, D., Hughes, S. & Thomas, D. Perceptions, experiences and opportunities for occupational safety and health professionals arising out of the COVID-19 Pandemic. *Hum. Soc. Sci. Commun.* **8**, 271 (2021).

21. Spotswood, E. N. et al. Nature inequity and higher COVID-19 case rates in less-green neighbourhoods in the United States. *Nat. Sustain.* **4**, 1092–1098 (2021).

22. Mardones, F. O. et al. The COVID-19 pandemic and global food security. *Front. Vet. Sci.* **7**, 578508 (2020).

23. Stephens, E. C., Martin, G., van Wijk, M., Timsina, J. & Snow, V. Impacts of COVID-19 on agricultural and food systems worldwide and on progress to the sustainable development goals. *Agric. Syst.* **183**, 102873 (2020).

24. Adhikari, J., Timsina, J., Khadka, S. R., Ghale, Y. & Ojha, H. COVID-19 impacts on agriculture and food systems in Nepal: Implications for SDGs. *Agric. Syst.* **186**, 102990 (2021).

25. Anholon, R, Rampasso, I. S., Silva, D. A. L., Filho, W. L. & Quelhas, O. L. G. The COVID-19 pandemic and the growing need to train engineers aligned to the sustainable development goals. *Int. J. Sustain. High. Educ.* **21**, 1269–1275 (2020).

26. Roberts, K. P. et al. Increased personal protective equipment litter as a result of COVID-19 measures. *Nat. Sustain.* **5**, 272–279 (2021).

27. Grewe, V. et al. Evaluating the climate impact of aviation emission scenarios towards the Paris agreement including COVID-19 effects. *Nat. Commun.* **12**, 3841 (2021).

28. Bertram, C. et al. COVID-19-induced low power demand and market forces starkly reduce CO_2 emissions. *Nat. Clim. Chang.* **11**, 193–196 (2021).

29. van Heerwaarden, C. C. et al. Record high solar irradiance in Western Europe during first COVID-19 lockdown largely due to unusual weather. *Commun. Earth Environ.* **2**, 37 (2021).

30. Fleetwood, J. Social justice, food loss, and the sustainable development goals in the era of COVID-19. *Sustainability* **12**, 5027 (2020).

31. The Government of Malaysia and PEMANDU Associates. Cut through the noise with the world's most comprehensive index on COVID-19. https://covid19.pemandu.org/about/ (2022).

32. World Bank. World Bank Country and Lending Groups. https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups?continueFlag=7006cdba6a014c64b241d709d4b7495b (2019).

33. Le Quéré, C. et al. Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement. *Nat. Clim. Chang.* **10**, 647–653 (2020).

34. Jeffrey, D. S., Christian, K., Guillaume, L., Fuller, G. & Woelm, F. *Sustainable development report 2021: the decade of action for the sustainable development goals* (Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN), 2021).

35. Sachs, J. et al. *Sustainable development report 2020: the sustainable development goals and COVID-19* (Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN), New York, 2020).

36. Poljanšek, K., Vernaccini, L. & Ferrer, M. M. *INFORM Covid-19 risk index* (Publications Office of the European Union, 2020).

37. The Lancet COVID-19 Commissioners, Task Force Chairs and Members, and Commission Secretariat. *Statement of the Lancet COVID-19 Commission: enhancing global cooperation to end the COVID-19 pandemic* (The Lancet COVID-19 Commissioners, Task Force Chairs and Members, and Commission Secretariat, 2021).

38. Jeffrey D. et al. *Sustainable development report 2022: from crisis to sustainable development: the SDGs as roadmap to 2030 and beyond* (Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN), 2022).

39. Sachs, J., Schmidt-Traub, G., Kroll, C., Lafortune, G. & Fuller, G. *Sustainable development report 2019: transformations to achieve the sustainable development goals* (Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN), 2019).

40. Chancel, L., Piketty, T., Saez, E. & Zucman, G. *World inequality repot 2022* (World Inequality Lab, 2022).

41. International Growth Centre. *The economic impact of COVID-19 lockdowns in sub-Saharan Africa* (International Growth Centre, 2020).

42. United Nations. *The sustainable development goals report 2021* (United Nations, 2021).

43. Executive Board of the United Nations Development Programme, the United Nations Population Fund, and the United Nations Office for Project Services. *UNDP strategic plan, 2022-2025* (Executive Board of the United Nations Development Programme, the United Nations Population Fund, and the United Nations Office for Project Services, 2021).

44. Sachs, J. D. et al. Six transformations to achieve the sustainable development goals. *Nat. Sustain.* **2**, 805–814 (2019).

45. Taylor, J. *Inequality in middle-income countries: analysis and suggestions* (International Research on Poverty Reduction, 2020).

46. International Monetary Fund. *World economic outlook* (International Monetary Fund, 2019). https://www.imf.org/en/Publications/WEO/weo-database/2019/October.

47. United Nations Economic and Social Council. *Progress towards the sustainable development goals* (United Nations Economic and Social Council, 2021).

48. Maire, J. et al. How different COVID-19 recovery paths affect human health, environmental sustainability, and food affordability: a modelling study. *Lancet Planet Health* **6**, e565–e576 (2022).

49. Editorials. Tracking progress on the SDGs. *Nat. Sustain.* **1**, 377 (2018).

50. International Monetary Fund. *World economic outlook: recovery during a pandemic—health concerns, supply disruptions* (International Monetary Fund, 2021).

51. Schmidt-Traub, G., Kroll, C., Teksoz, K., Durand-Delacre, D. & Sachs, J. D. National baselines for the Sustainable Development Goals assessed in the SDG Index and Dashboards. *Nat. Geosci.* **10**, 547–555 (2017).

52. Xu, Z. et al. Assessing progress towards sustainable development over space and time. *Nature* **577**, 74–78 (2020).

Acknowledgements

Author contributions

H.Y., X.W., T.W. and Y.G. designed the research. H.Y. and X.W. performed the data analysis. H.Y., X.W., L.G., T.W., B.L., D.F. and Y.G. contributed to the interpretation of results, writing, and editing the paper.

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/s43247-023-00846-x.

Correspondence and requests for materials should be addressed to Tao Wang.

Peer review information *Communications Earth & Environment* thanks Kalterina Shulla and Prajal Pradhan for their contribution to the peer review of this work. Primary Handling Editor: Aliénor Lavergne. Peer reviewer reports are available.

Reprints and permission information is available at http://www.nature.com/reprints

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.