Article

Quantitative assessment of The Group of Seven's collaboration in sustainable development goals

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Strengthening international collaboration is essential to achieving the United Nations' SDGs. The Group of Seven (G7) is recognized for acting and enhancing cooperation to achieve the SDGs. However, the current understanding of G7's cooperation is rather subjective without quantitative measurements. Here we show a comprehensive and quantitative analysis of G7's cooperation with regards to the economic and environmental SDGs over the period of 2000-2020. The results suggest that G7 countries have all contributed positively to economic indicators thanks to their closely binding relationship. By contrast, significant discrepancies and uncooperative performances in environmental indicators have been revealed. Particularly, Canada and Germany have shown considerable negative synergy contributions to environmental indicators, which might offset the positive contributions brought by France and Italy and lead to an overall negative synergy. Our results highlight the need for further collaboration among G7 to tackle emerging environmental issues, such as climate change and shrinking biodiversity.

Introduction

The United Nations General Assembly adopted the 2030 Agenda for Sustainable Development in 2015 to provide a shared blueprint and prosperity for people and the planet, both in the present and future. Building on the principle of "leaving no one behind," the 2030 Agenda contains 17 Sustainable Development Goals (SDGs), is an urgent call to action by all countries in global partnership to achieve sustainable development for all[1]. Currently, many countries have enacted plans and policies to reach these goals using scientific information and relevant programs[2,3]; however, some others are facing challenges in meeting their objectives due to political and economic reasons[4], leading to intensifying the uncooperative nature of countries in achieving the 2030 Agenda. According to the Intergovernmental Panel on Climate Change (IPCC), inclusive, collaborative, and synergistic actions must be taken by all nations in order to achieve the 1.5 °C global

warming target and the 2030 Agenda[5]. The latest IPCC report indicated that resilient climate development is critically important for achieving the Nationally Determined Contributions (NDCs) by increasing international cooperation and enhancing access to financial resources[6,7]. Countries with extensive cooperation and synchronized policymaking can play various leadership roles by positively progressing toward their sustainable goals.

The Paris Agreement has also emphasized the importance of international cooperation between countries to support policymakers in their decision-making, such as enhancing domestic and foreign policies and addressing climate crises. Specifically, (i) Article 7.7.c encourages parties to strengthen scientific knowledge on climate, including research, systematic observation of the climate system, and early warning systems, to inform climate services and support decision-making; (ii) Article 8.4 states that cooperation within

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communities is essential as it enhances the understanding, action, and support within these communities; and (iii) Article 11 describes that capacity-building in parties should be country-driven based on their unique needs; meanwhile, all developed countries should offer support to developing countries. Hence, to strengthen this cooperation, it is no doubt that each country must work towards fulfilling its development goals by borrowing and lending support from one another.

Although the importance of international cooperation has been widely recognized, it has been highly challenging to quantitatively measure the level of cooperation among countries due to the widespread nature of SDGs. In particular, previous studies are primarily focused on measuring isolated national efforts and commitments to specific targets without capturing the dynamic and collective interactions of international cooperation[8–11]. In the meantime, the importance of strengthening international collaboration has been widely recognized to help achieve SDGs[12–15], which emphasizes an urgent need for a quantitative approach to adequately measure the interactive and cumulative efforts of countries working together towards their goals. Here we aim to address this challenge by proposing a novel methodological framework based on synergy. The term synergy originates from the Greek word for "working together." It represents a combination of different actions or elements that strengthen each other, leading to a more significant result than the sum of individual achievements. This synergy-based framework allows for a quantitative measurement of the level of international cooperation towards SDGs and a detailed breakdown of synergy contribution from individual countries (whether a country plays a positive or negative role in implementing SDGs).

As the most advanced and industrialized economies globally, the G7 (Group of Seven), including Canada, France, Germany, Italy, Japan, the United Kingdom (UK), and the United States (US), are considered in this study to provide a comprehensive assessment of their collaboration progress towards the SDGs. As stated in the G7's 2016 Communiqué, the environmental ministers affirmed a solid collaboration to act on achieving their SDGs and environmental issues in and beyond the G7 members[16]. Despite this, recent studies indicate that the G7 countries have yet to fully integrate the SDGs into their domestic policies or inter-member relations[17]. The growth and stabilization of economies have often taken precedence over pursuing SDGs at the national policy level[18]. The COVID-19 pandemic showed that the G7 must avoid returning to "business as usual" investment patterns and activities and make their economies more socially equitable and environmentally sustainable[19]. Therefore, to address the climate issue and achieve SDGs, G7 countries must implement integrated sustainable development plans and policies to avoid or minimize the actual or possible impacts on all SDGs for various sectors and communities[20].

The concept of synergy holds paramount importance in policy and decision-making processes, particularly in the context of achieving SDGs, which necessitate collaborative efforts harnessing the strengths and capabilities of multiple countries. By quantitatively measuring synergy among multiple countries, which provides an accurate reflection of policy outcomes, this study can help gain a deeper understanding of how decisions affect countries' progress towards the SDGs. This understanding not only informs current policymaking but also enables retrospective decisions such as allowing us to review past "successful" policies and enhance (if needed) current policies for future iterations. Such a reflective approach fosters continuous improvement in policy implementation, ensuring that strategies are adaptive and responsive to evolving challenges and opportunities.

Results
Domestic changes
We begin with quantifying the domestic changes in SDG indicators for G7, which are associated with the various social, economic, political, cultural, and environmental issues experienced by individual countries. Note that the 42 SDG indicators considered in this study (see Table 1) are classified into two groups: economic (SDGs 1-9) and environmental (SDGs 12–15), to facilitate the result analysis. Fig. 1 shows the average domestic changes for G7 countries in economic and environmental SDG indicators. It can be seen that there is a synchronized pattern of domestic change in economic indicators across G7 countries during the last two decades. Notably, there are significant oscillations between 2008 and 2012, as well as in 2020, with significant changes found in Germany and Japan. These oscillations are due to the global financial crisis (i.e., the Great Recession) between 2007 and 2009, and the COVID-19 pandemic starting in 2020; these events have caused immense disputes in domestic finances for most countries around the world. Aside from France, similar fluctuating patterns of rebounding rates can be found throughout the G7 in the aftermath of the Great Recession; particularly between 2010 and 2011, the US and Canada demonstrate faster economic rebound potential, although Japan is likely to be slower. In comparison, the environmental SDG indicators manifest considerable fluctuation among G7 countries. For instance, a tremendous instability is reported for Japan between 2011 and 2012 due to a historical natural disaster, the 9.0 Richter 2011 Tōhoku earthquake, leading to significant loss of life and environmental destruction in Japan. Similarly, France and Germany have also experienced rapid environmental changes in the past two decades, while Canada appears to have the least environmental changes among G7 countries. Various factors can cause these unstable environmental conditions, the most important ones are climate change, pollution, energy production, and land use change.

The detailed domestic changes in the 42 SDG indicators are further presented in Fig. 2 and Supplementary Figs S1–S6 (in supporting information). Most of the economic indicators (e.g., SDGs 8.1.1, 8.2.1, and 8.5.2) have fluctuated significantly during the Great Recession in 2008 and the COVID-19 pandemic in 2020. The consequences of these events greatly impacted the G7 economies, particularly Japan and Germany during the Great Recession and the UK, Italy, and France during the COVID-19 outbreak. The economy of Japan took longer to rebound and its GDP did not reach pre-recession levels until 2014. In contrast, Germany's economy recovered much faster, with its GDP surpassing pre-recession levels by 2011[21,22]. Canada and the US are also among the quick-recovering countries after the Great Recession; nevertheless, their unemployment rates remained relatively high, with the most dramatic increases occurring in 2009 and 2020. The results also show that the COVID-19 outbreak has caused more significant impacts on the GDP growth of G7 countries than the Great Recession. In particular, the UK, Italy, and France experienced the most significant economic contraction during the COVID-19 pandemic. According to the UK's Office for National Statistics, the Italian National Institute of Statistics, and the French National Institute of Statistics and Economic Studies, the UK's GDP contracted by 9.9% in 2020 - the most significant annual contraction on record, while Italy and France's GDP contracted by 8.9% and 8.2%, respectively[23–25]. As for environment indicators, Fig. 2 shows a significant change in Japan's death rate due to natural disasters. In particular, the Tōhoku earthquake in 2011 and the resulting tsunami killed approximately 15,000 people, with many more injured and missing[26,27]. In comparison, the rest of the G7 countries shows a minimal change in natural disaster death rate over the past 20 years. With respect to the forested areas, there is a slight trend change after the Great Recession in most countries except Canada. Canada's forested area have remained relatively stable during the last thirty years due to its effective forest management policies and practices[28,29]. Similarly, the US has made steady progress in biodiversity conservation in protected areas thanks to its Endangered Species Act[30], which emphasizes the protection of endangered species and their habitats, including those found in mountain ecosystems. Overall, the consistent pattern in economic indicators demonstrates the closely binding relationship of G7 countries, while significant variations and

Table 1 | List of 42 SDG indicators selected in this study and their goal directions

SDG Indicator	Goal Direction
SDG 1: End poverty in all its forms everywhere.	
▪ *Indicator 1.1.1*: Proportion of the population living below the international poverty line by sex, age, employment status and geographic location (urban/rural).	−
▪ *Indicator 1.A.1*: Proportion of domestically generated resources allocated by the government directly to poverty reduction programmes.	
○ *Series 1*: Share of Gross National Income (GNI) donated towards poverty reduction.	+
▪ *Indicator 1.A.2*: Proportion of total government spending on essential services (education, health, and social protection).	
○ *Series 1*: Health spending as a share of total government expenditure.	+
SDG 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture.	
▪ *Indicator 2.5.2*: Proportion of local breeds classified as being at risk, not at risk or at unknown level of risk of extinction.	−
SDG 3: Ensure healthy lives and promote well-being for all at all ages.	
▪ *Indicator 3.1.1*: Maternal mortality ratio.	−
▪ *Indicator 3.2.1*: Under-5 mortality rate.	−
▪ *Indicator 3.2.2*: Neonatal mortality rate.	−
▪ *Indicator 3.3.2*: Tuberculosis incidence per 100,000 population.	−
▪ *Indicator 3.4.1*: Mortality rate attributed to cardiovascular disease, cancer, diabetes, or chronic respiratory disease.	−
▪ *Indicator 3.4.2*: Suicide mortality rate.	−
▪ *Indicator 3.6.1.1*: Death rate due to road traffic injuries.	
○ *Series 1*: Road traffic deaths.	−
▪ *Indicator 3.B.1*: Proportion of the target population covered by all vaccines included in their national programme.	
○ *Series 1*: Share of children fully vaccinated against measles.	+
SDG 6: Ensure access to water and sanitation for all.	
▪ *Indicator 6.1.1*: Proportion of population using safely managed drinking water services.	
○ *Series 1*: Share of the population using safely managed drinking water.	+
▪ *Indicator 6.2.1*: Proportion of population using (a) safely managed sanitation services and (b) a hand-washing facility with soap and water.	
○ *Series 1*: Share of the population using safely managed sanitation facilities.	+
SDG 7: Ensure access to affordable, reliable, sustainable, and modern energy for all.	
▪ *Indicator 7.1.1*: Proportion of population with access to electricity.	+
▪ *Indicator 7.1.2*: Proportion of population with primary reliance on clean fuels and technology.	+
▪ *Indicator 7.2.1*: Renewable energy share in the total final energy consumption.	+
▪ *Indicator 7.3.1*: Energy intensity measured in terms of primary energy and GDP.	−
SDG 8: Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all.	
▪ *Indicator 8.1.1*: Annual growth rate of real GDP per capital.	+
▪ *Indicator 8.2.1*: Annual growth rate of real GDP per employed person.	+
▪ *Indicator 8.4.2*: Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP.	
○ *Series 1*: Domestic material consumption per capita.	−
○ *Series 2*: Domestic material consumption per unit of GDP.	−
▪ *Indicator 8.5.2*: Unemployment rate, by sex, age, and persons with disabilities.	
○ *Series 1*: Unemployment rate.	−
SDG 9: Build resilient infrastructure, promote inclusive and sustainable Industrialization and foster innovation.	
▪ *Indicator 9.1.2*: Passenger and freight volumes, by mode of transport.	
○ *Series 1*: Air passengers carried.	−
○ *Series 2*: Railway passengers carried.	+
○ *Series 3*: Air transport, freight (ton-km).	+
▪ *Indicator 9.2.1*: Manufacturing value added as a proportion of GDP and per capita.	+
▪ *Indicator 9.2.2*: Manufacturing employment as a proportion of total employment.	
○ *Series 1*: Industry employment as a share of total employment.	+
○ *Series 2*: Manufacturing employment as a share of total employment.	+
▪ *Indicator 9.4.1*: CO_2 emission per unit of value added.	−
▪ *Indicator 9.5.1*: Research and development expenditure as a proportion of GDP.	+
▪ *Indicator 9.5.2*: Researchers (in full-time equivalent) per million inhabitants.	+
▪ *Indicator 9.C.1*: Proportion of population covered by a mobile network, by technology.	
○ *Series 1*: Mobile phone subscriptions per 100 people.	+
○ *Series 2*: Share of the population using the Internet.	+
SDG 12: Ensure sustainable consumption and production patterns.	
▪ *Indicator 12.2.2*: Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP.	

Table 1 (continued) | List of 42 SDG indicators selected in this study and their goal directions

SDG Indicator	Goal Direction
○ *Series 1*: Domestic material consumption per capita.	–
○ *Series 2*: Domestic material consumption per unit of GDP.	–
SDG 13: Take urgent action to combat climate change and its impacts.	
■ *Indicator 13.1.1*: Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population.	
○ *Series 1*: Death rate from natural disasters.	–
SDG 14: Conserve and sustainably use the oceans, seas, and marine resources for sustainable development.	
■ *Indicator 14.1.1*: Index of coastal eutrophication and plastic debris density.	
○ *Series 1*: Chlorophyll-a deviation from the global average.	–
SDG 15: Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss.	
■ *Indicator 15.1.1*: Forest area as a proportion of total land area.	+
■ *Indicator 15.1.2*: Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type.	
○ *Series 1*: Proportion of important sites for freshwater biodiversity that are covered by protected areas.	+
■ *Indicator 15.4.1*: Coverage by protected areas of important sites for mountain biodiversity.	+
■ *Indicator 15.A.1*: Official development assistance and public expenditure on conservation and sustainable use of biodiversity and ecosystems.	
○ *Series 1*: Total amount donated for biodiversity conservation in developing countries	+

Note a sign of "+" indicates that the goal is to increase the value of an SDG indicator, while a sign of "–" means the goal is to reduce the indicator.
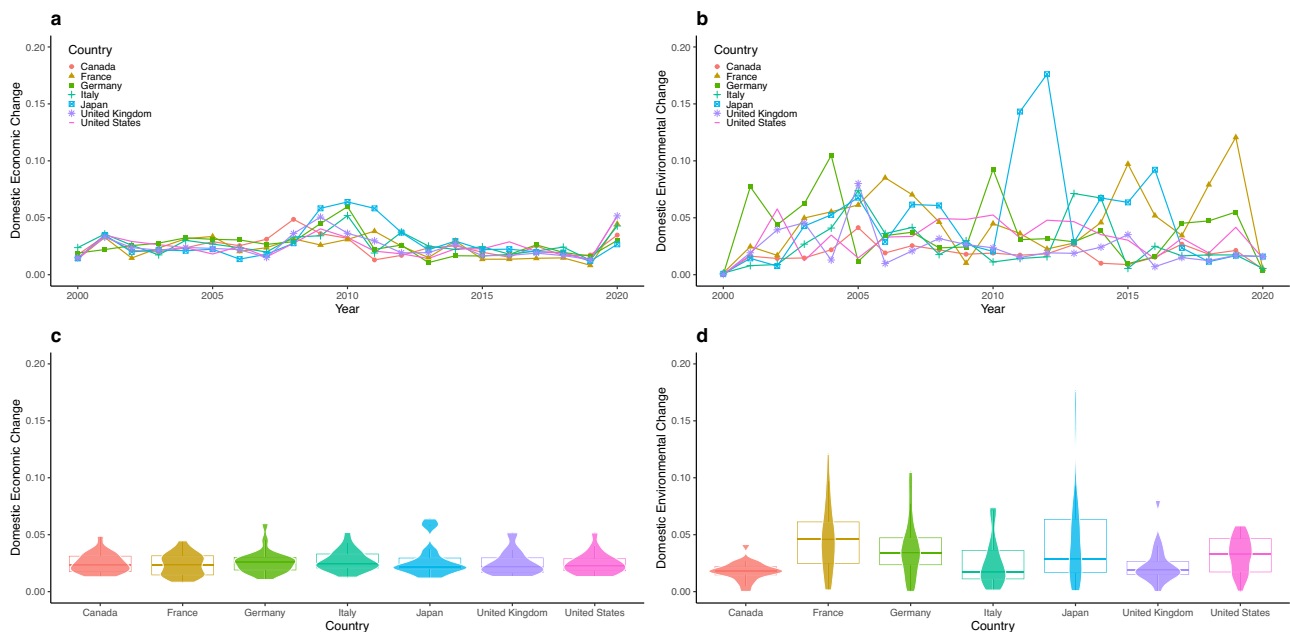
Fig. 1 | Domestic changes in both economic and environmental SDG indicators for G7 countries. Note that **a** and **b** show the averaged domestic changes throughout the evaluation period of 2000–2020, **c** and **d** show the distribution of domestic changes.

differences in environmental indicators are clearly reported among G7 countries.

Gross Synergy

Gross synergy assesses the level of cooperation among countries in achieving the SDGs. If a group of countries improves their SDG indicators towards the expected direction, their gross synergy grows and becomes positive. In contrast, if the countries work entirely against each other or in opposition to the sustainable goals, their gross synergy will be negative. Fig. 3 presents the gross synergies for all SDG indicators among G7 countries throughout 2000-2020. The percentage of years with positive gross synergy are shown in Fig. 4 to help understand whether G7 countries have been cooperating to improve all SDG indicators.

The results show that the gross synergies of most SDG indicators have been fluctuating around zero, with more positive synergies than negative throughout the period of 2000-2020. This suggests that, although G7 countries do collaborate on the majority of SDG indicators, there are still some disputes or differences in other SDG indicators. For instance, during the Great Recession in 2008 and the recent COVID-19 outbreak, the economic synergies of G7 have fluctuated significantly. In particular, a positive synergy of 0.269 in 2010 indicates that the G7 countries have rebounded together from the Great Recession in 2008, while a negative synergy of 0.294 in 2020 is a direct reflection of the enormous impacts of the COVID-19 outbreak on the G7 economies. These extremely high economic synergies among G7 further confirms their strong bonding relationship in economic development. Zero gross synergies are viewed as either no progress or

Fig. 2 | Domestic changes for G7 in six selected SDG indicators. a SDG 8.1.1 – annual growth rate of real GDP per capital, (**b**) SDG 13.1.1(1) - death rate from natural disasters, (**c**) SDG 8.2.1 - annual growth rate of real GDP per employed person, (**d**) SDG 15.1.1 - forest area as a proportion of total land area, (**e**) SDG 8.5.2(1) - unemployment rate, and (**f**) SDG 15.4.1 - coverage by protected areas of important sites for mountain biodiversity.
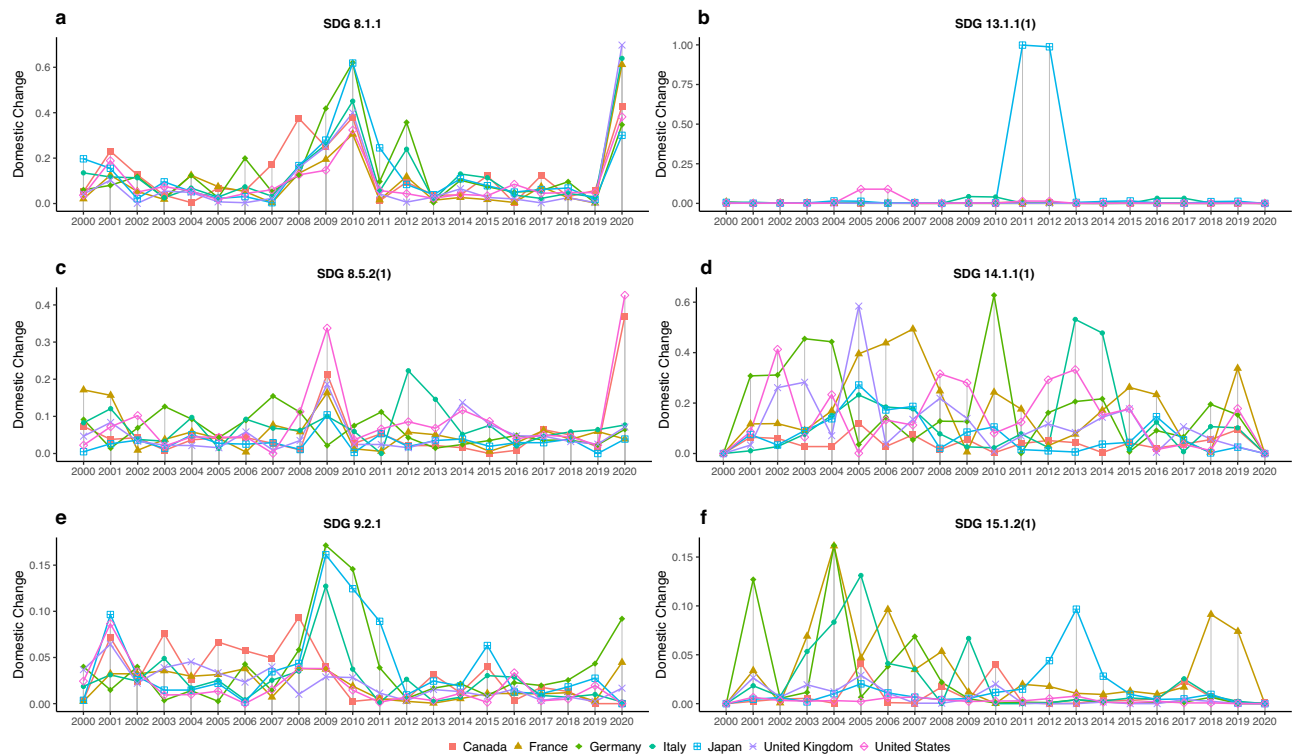

	Indicators	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Average
Economic	SDG.1.1.1	0.007	0.004	0.004	-0.013	0.012	-0.003	0.002	-0.003	-0.004	0.030	-0.016	-0.020	-0.015	-0.022	0.025	-0.012	0.021	-0.031	0.013	0.000	NA	-0.001
	SDG.1.A.1(1)	NA	0	-0.041	0.026	0	0.056	0.041	0	0.075	0	0	-0.041	0	0	-0.026	0	0.012	0.012	-0.012	0.026	0	0.006
	SDG.1.A.2(1)	NA	0.019	0.016	0.009	0.022	0.009	0.013	0.010	-0.010	0.005	0.010	0.021	0.017	0.014	0.018	0.016	0.007	0.008	0.004	0.006	NA	0.011
	SDG.2.5.2	NA	-0.021	-0.002	-0.006	-0.018	-0.015	-0.007	-0.005	0.025	-0.020	0.007	-0.016	0.016	-0.015	0.031	-0.013	-0.011	-0.005	-0.010	0.009	-0.005	-0.003
	SDG.3.1.1	NA	-0.023	0	0.011	0	-0.005	0	0	0.005	0	0	0.017	0	0	0	0.011	0	NA	NA	NA	NA	0.001
	SDG.3.2.1	0.017	0.013	0.013	0.011	0.009	0.012	0.011	0.009	0.009	0.009	0.013	0.006	0.013	0.006	0.007	0.006	0.005	0.006	0.006	0.006	0.006	0.009
	SDG.3.2.2	0.003	0.012	0.005	0.006	0.010	0.007	0.007	0.010	0.005	0.002	0.013	0.002	0.002	0.007	0.005	0.002	0.005	0.007	0.005	0.003	0.013	0.006
	SDG.3.3.2	NA	0.024	0.011	0.004	0.012	0.012	0.005	0.011	-0.004	0.006	0.009	0.006	0.008	0.006	0.006	0.009	-0.003	0.006	0.004	0.007	0.012	0.008
	SDG.3.4.1	NA	0.027	0.016	0.017	0.032	0.016	0.024	0.010	0.016	0.013	0.016	0.014	0.012	0.015	0.013	0.003	0.008	0.013	0.007	NA	NA	0.015
	SDG.3.4.2	NA	0.011	-0.007	-0.010	0.015	0.011	0.011	-0.011	-0.008	-0.007	0.008	0.013	0.010	-0.010	0.017	0.009	0.023	-0.017	0.011	0.012	NA	0.004
	SDG.3.6.1(1)	0.005	0.004	0.004	0.003	0.006	0.003	0.004	0.004	0.004	0.004	0.004	0.003	0.003	0.002	0.002	-0.001	-0.001	0.001	0.001	0.001	NA	0.003
	SDG.3.B.1(1)	NA	-0.003	0	0.009	0.004	0.003	0	0.003	0.002	0.021	0.015	0.020	0.010	0.014	0.013	0.006	0.005	0.013	0.013	0.010	-0.012	0.007
	SDG.6.1.1(1)	NA	0.001	0.000	0.004	0.006	0.006	0.007	0.004	0.004	0.004	0.007	0.007	0.007	0.007	0.008	0.006	0.006	0.006	0.006	0.003	0	0.005
	SDG.6.2.1(1)	NA	0.000	0.001	0.002	0.003	0.003	0.002	0.003	0.003	0.003	0.003	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.000	0.002
	SDG.7.1.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SDG.7.1.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SDG.7.2.1	NA	-0.008	0.008	0.013	0.007	0.012	0.012	0.014	0.017	0.016	0.011	0.018	0.021	0.017	0.012	0.012	0.011	0.015	0.018	0.013	NA	0.013
	SDG.7.3.1	NA	0.009	-0.008	0.006	0.009	0.011	0.014	0.005	0.006	0.004	0.017	0.005	0.005	0.009	0.004	0.005	0.005	0.005	0.009	0.004	NA	0.013
	SDG.8.1.1	0.041	-0.086	-0.038	0.027	0.038	-0.019	0.033	0.022	-0.104	-0.155	0.269	-0.035	-0.068	0.013	0.042	0.038	-0.019	0.030	-0.028	-0.011	-0.294	-0.015
	SDG.8.2.1	NA	-0.071	0.030	-0.021	0.046	-0.070	0.040	0.028	-0.097	-0.083	0.223	-0.064	0.061	0.023	0.033	-0.025	-0.028	0.041	-0.029	-0.185	NA	-0.015
	SDG.8.4.2(1)	0.007	0.007	0.004	-0.008	0.007	-0.004	-0.009	0.011	0.014	-0.004	-0.004	0.006	-0.002	0.007	0.003	0.003	-0.003	0.004	0.003	NA	NA	0.002
	SDG.8.4.2(2)	NA	0.012	0.006	0.007	0.006	0.010	-0.003	0.009	0.009	0.014	0.005	-0.003	0.006	-0.003	0.007	0.005	0.004	-0.005	0.007	0.005	NA	0.004
	SDG.8.5.2(1)	0.038	0.040	-0.026	-0.017	0.034	0.019	0.029	0.025	-0.031	-0.091	-0.018	0.023	-0.030	-0.028	0.032	0.022	0.019	0.029	0.026	0.016	-0.072	0.002
	SDG.9.1.2(1)	-0.004	0.001	0.004	-0.005	-0.004	-0.004	-0.002	-0.003	0.002	0.003	-0.006	-0.005	-0.002	-0.002	-0.002	-0.003	-0.003	-0.004	-0.003	-0.004	0.059	0.001
	SDG.9.1.2(2)	0.002	0.001	-0.002	0.001	0.002	0.002	0.003	0.003	0.002	-0.001	0.001	0.002	0.002	0.002	0.002	0.002	0.003	0.001	NA	NA	NA	0.002
	SDG.9.1.2(3)	0.005	-0.007	0.005	0.002	0.007	-0.002	0.003	0.003	-0.003	-0.016	-0.023	-0.002	-0.004	-0.004	0.004	-0.002	0.003	0.011	0.005	-0.004	-0.021	-0.002
	SDG.9.2.1	-0.010	-0.033	-0.018	-0.017	-0.013	-0.015	-0.012	-0.015	-0.026	-0.047	0.025	-0.008	-0.004	-0.007	0.007	0.012	-0.010	-0.006	-0.007	-0.007	-0.007	-0.010
	SDG.9.2.2(1)	-0.013	-0.015	-0.017	-0.021	-0.017	-0.011	-0.007	-0.008	-0.014	-0.027	-0.019	0.004	-0.010	-0.010	-0.010	-0.006	-0.005	-0.003	NA	NA	NA	-0.012
	SDG.9.2.2(2)	NA	-0.012	-0.012	-0.021	-0.014	-0.017	-0.012	-0.007	-0.033	-0.035	-0.013	0	-0.006	-0.004	-0.007	-0.005	-0.005	-0.004	-0.007	-0.005	0.008	-0.011
	SDG.9.4.1	0.011	0.010	0.011	0.005	0.013	0.013	0.018	0.013	0.013	0.015	-0.003	0.021	0.007	0.008	0.020	0.009	0.010	0.011	0.008	NA	NA	0.011
	SDG.9.5.1	0.009	0.010	0.010	-0.006	-0.008	0.006	0.008	0.010	0.011	0.021	-0.010	0.008	-0.013	0.011	0.008	-0.005	-0.009	0.010	0.010	NA	NA	0.004
	SDG.9.5.2	0.011	0.012	0.014	0.021	0.012	0.017	0.011	0.013	0.016	0.015	0.013	0.012	0.013	0.010	0.012	0.016	0.012	0.015	0.009	NA	NA	0.013
	SDG.9.C.1(1)	0.065	0.037	0.017	0.024	0.029	0.032	0.030	0.032	0.013	0.008	-0.019	0.013	0.009	0.009	0.019	0.012	0.013	0.011	-0.015	0.011	-0.011	0.016
	SDG.9.C.1(2)	0.058	0.045	0.053	0.027	0.029	0.027	0.014	0.035	0.019	0.012	0.007	0.011	0.019	0.012	0.015	0.020	0.011	0.012	0.010	-0.014		0.021
	Average	**0.014**	**0.001**	**0.002**	**0.002**	**0.008**	**0.004**	**0.008**	**0.007**	**-0.002**	**-0.007**	**0.016**	**0.001**	**0.000**	**0.002**	**0.010**	**0.004**	**0.003**	**0.006**	**0.002**	**0.003**	**-0.028**	**0.003**
Environmental	SDG.12.2.2(1)	NA	0.007	0.007	0.004	-0.008	0.007	-0.004	-0.009	0.011	0.014	-0.004	-0.004	0.006	-0.002	0.007	0.003	0.003	-0.003	0.004	0.003	NA	0.002
	SDG.12.2.2(2)	NA	0.012	0.006	0.007	-0.006	0.010	-0.003	0.009	0.009	0.014	0.005	-0.003	0.006	-0.003	0.007	0.005	0.004	-0.005	0.007	0.005	NA	0.004
	SDG.13.1.1(1)	0.002	0.001	-0.001	-0.001	-0.001	-0.003	0.001	0.001	0.000	-0.001	0.002	-0.003	0.003	0.001	0.000	0.000	-0.001	0.001	-0.001	0.001	NA	0.000
	SDG.14.1.1(1)	NA	-0.048	-0.090	0.075	-0.094	0.120	0.085	-0.092	-0.078	-0.052	0.058	-0.037	0.047	-0.087	0.087	0.051	0.046	0.029	-0.028	-0.069	NA	-0.004
	SDG.15.1.1	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.001
	SDG.15.1.2(1)	NA	0.012	0.003	0.010	0.027	0.018	0.013	0.010	0.006	0.004	0.004	0.004	0.002	0.003	0.004	0.003	0.002	0.002	0.005	0.005	0.001	0.007
	SDG.15.4.1	NA	0.014	0.003	0.019	0.017	0.004	0.019	0.009	0.005	0.004	0.005	0.002	0.001	0.003	0.002	0.003	0.003	0.004	0.003	0.001	0	0.006
	SDG.15.A.1(1)	NA	NA	NA	0.007	-0.014	0.017	0.006	0.022	-0.010	0.012	0.039	-0.043	-0.031	0.046	0.063	-0.041	0.060	-0.043	-0.077	-0.041		0.001
	Average	**0.001**	**0.000**	**-0.010**	**0.015**	**-0.010**	**0.022**	**0.015**	**-0.006**	**-0.007**	**-0.001**	**0.014**	**-0.001**	**0.003**	**-0.014**	**0.019**	**0.016**	**0.002**	**0.011**	**-0.007**	**-0.017**	**-0.010**	**0.002**

Color codes for synergy values:

-0.15 -0.10 -0.05 0 0.05 0.10 0.15

0	= 0 (no synergy)		NA	= NA (no value due to the lack of data)

0.000 — The true value is very close to 0 but still greater than 0; it is displayed as 0.000 due to rounding.
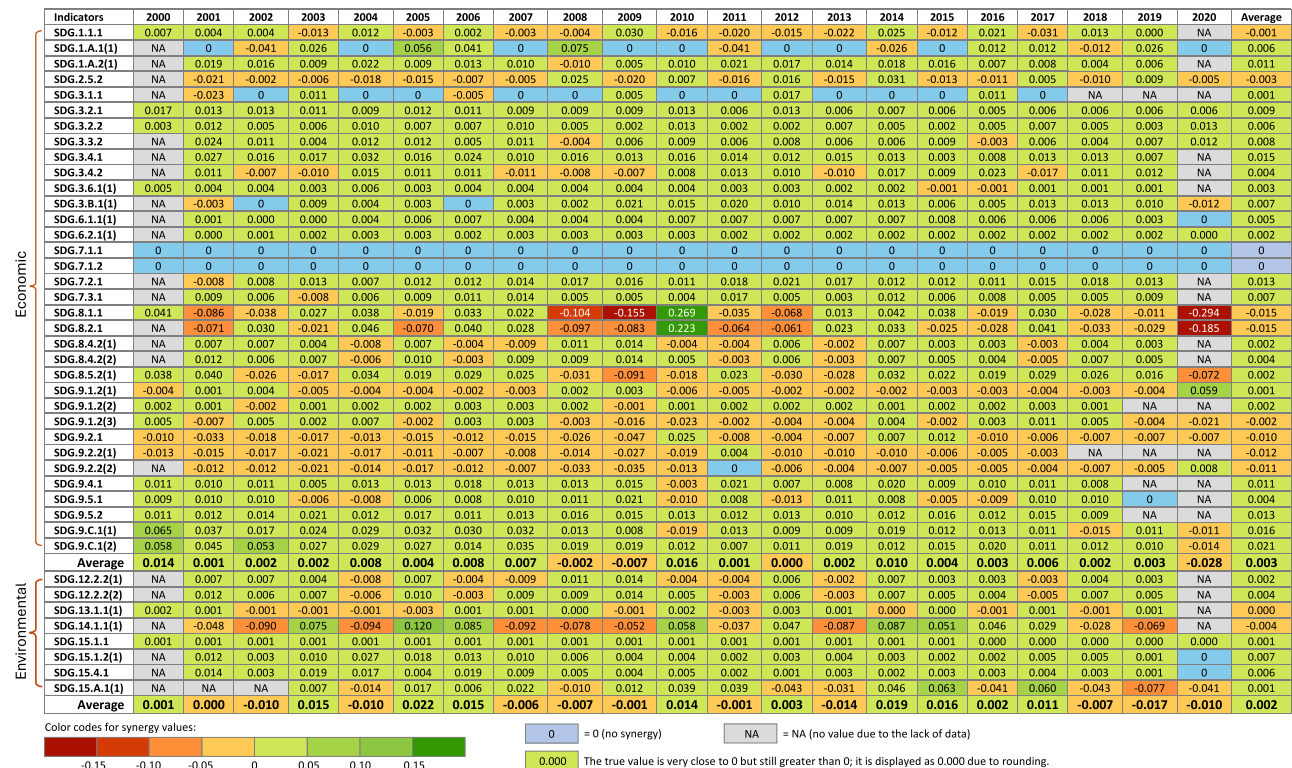
Fig. 3 | G7 synergies for 42 SDG indicators during the period of 2000-2020. Note that the SDG indicators are grouped into economic and environmental indicators and the average synergy for each group is calculated (see the two rows named as "Average") to help understand the overall cooperation among the G7 countries. The column named "Average" shows the average synergies for individual indicators over the period of 2000–2020.
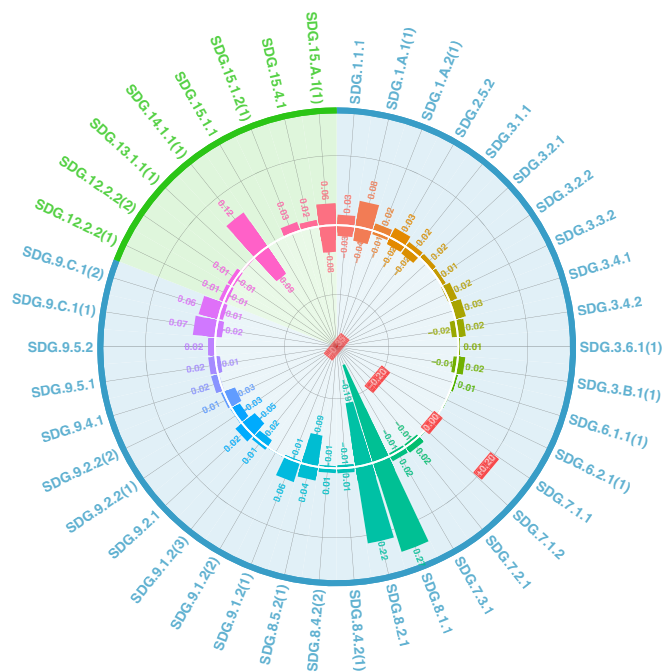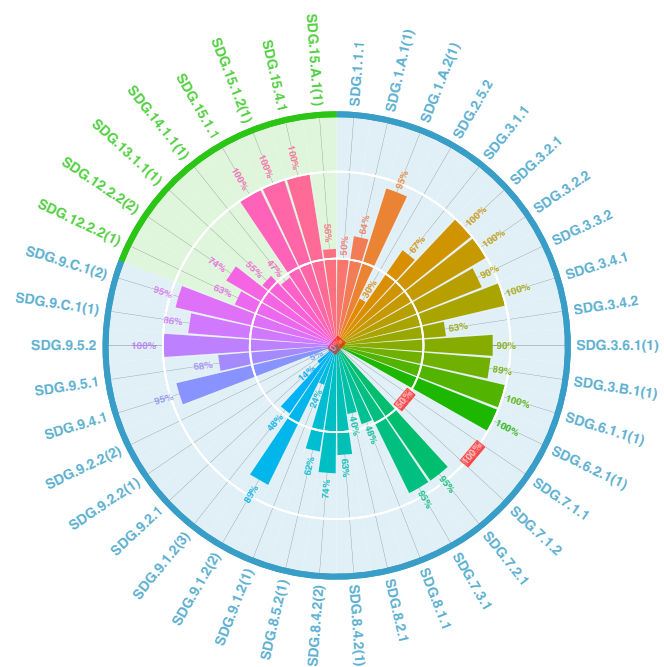
Fig. 4 | Gross synergies of 42 SDG indicators among G7 countries over the period of 2000-2020. a shows the range of gross synergies throughout the entire period; and **b** presents the percentage of years with positive gross synergy throughout the entire period. Here we use 50% as a threshold to determine whether the G7 member countries have been working together to improve the SDG indicator towards its goal direction.

offset between domestic and foreign changes. Here we should note that SDGs 7.1.1 (proportion of the population with access to electricity) and 7.1.2 (proportion of the population with primary reliance on clean fuels and technology) are linked to this situation where synergy equals zero over the entire period. This can be explained by the fact that G7 countries already have full access to electricity and advanced technologies, thus no further progress needs to be made. As for environmental indicators, SDG 14.1.1(1) (chlorophyll-a deviation from the global average) shows considerable changes in gross synergy, varying from −0.094 to +0.120. Chlorophyll-a is a widely used proxy for phytoplankton biomass and an indication of changes in phytoplankton production in the protection of marine pollution[31]. The considerable changes in this indicator may indicate that the G7 countries have been facing significant challenges in tackling marine pollution. In comparison, other environmental SDG indicators are mostly presenting positive but very small synergies, suggesting that more cooperation among the G7 countries is needed to achieve the environmental goals.

As presented in Fig. 4, the G7 countries have been working together to improve most of the SDG indicators, however, there are still some indicators requiring more collaboration. In detail, the G7 has been working closely to end poverty (i.e., SDG 1) ensure healthy lives, and promote well-being (i.e., SDG 3); but only little progress has been made among G7 in reducing the proportion of local breeds classified as being at risk of extinction (i.e., SDG 2.5.2), which may pose potential threats to their food security in a long run. As a group of the most developed countries around the world, the G7 has made significant collaborative efforts to ensure the availability and sustainable management of water and sanitation (SDG 6) and to promote renewable energy while ensuring access to affordable and reliable energy (SDG 7). As for economic growth (i.e., SDG 8), the G7 has been cooperating to lower their unemployment rate and domestic material consumption and to increase GDP per employed person; however, significant fluctuations in GDP per capital have been recorded for G7 due to the Great Recession in 2008 and the COVID-19 pandemic in 2020. It is also worth mentioning that the increasing dependence of the G7 economies on other fast-growing economies (e.g., China and India) over the past two decades could be another factor for such fluctuations[32,33]. The results also show that the G7 has been working together to reduce carbon emissions, invest in research and development, and expand the coverage of mobile network and the Internet under SDG 9. As for the mode of transport, the number of railway passengers in most of the G7 countries has been increasing but people in other countries (e.g., Canada and the US) are still heavily relying on air transport, which is a concerning issue from a carbon reduction perspective. The G7 has shown a significant decline in domestic manufacturing industries due to the shift to China and other Southeast Asia countries. In terms of environmental SDG indicators, the results show that the G7 has been collaborating at certain levels to ensure sustainable consumption and production (i.e., SDG 12) and to protect ecosystems, forests, and biodiversity (i.e., SDG 15); however, more cooperative efforts are needed among the G7 to combat climate change and protect the marine environment.

Synergy contributions from individual countries

It is essential to determine the synergy contributions from individual countries in order to further understand the level of cooperation within the G7 countries. The contributions from individual members will assist policymakers in identifying, documenting, and integrating policies shared across G7 countries to help achieve their SDGs. Figure 5 and Supplementary Fig S7–S12 (see supporting information) show comprehensive comparisons of synergy contributions for 42 SDG indicators during the period of 2000–2020. The contributions from individual countries can vary significantly by indicators and years. For example, in the year of 2020, the G7 economies experienced significant GDP losses due to the COVID-19 pandemic (as reflected by a

negative gross synergy of -0.294 in SDG 8.1.1). All G7 member countries contributed negatively to the GDP losses, with the UK contributing the most (by −24.5%) and Japan contributing the least (by -5.3%). While the COVID-19 pandemic lockdown is the primary reason for the GDP losses, it is worth noting that major domestic changes in political structure and economic policy can also cause significant fluctuations in GDP growth. For example, the Brexit process initiated in 2016 has brought significant uncertainty for businesses and investors, resulting in lower investment and slower economic growth in the United Kingdom[34]. In comparison to the GDP losses, the G7's unemployment rate [i.e., SDG 8.5.2(1)] in 2020 experienced a certain level of decline, with individual countries showing opposite trends due to their domestic differences in workforce structure and labour market [as reflected by a negative gross synergy of −0.072 in SDG 8.5.2(1)]. In particular, the US and Canada made significant negative contributions (−67.7% and −56.6%) to the G7's overall unemployment rate; although the other 5 countries (i.e., Japan, France, Germany, the UK, and Italy) did contribute positively, their contributions were not large enough to offset the negative contributions by the US and Canada.

Considering that the synergy contributions tend to present some extreme values, here we choose to use the statistical term of "median" to help synthesize the various contributions by indicators, years, and countries. In particular, we further calculate the median contributions by countries in order to summarize the general roles of individual countries in each SDG indicator over the period of 2000-2020 (shown at the bottom of each subplot in Fig. 5 and Supplementary Figs S7–S12). It can be seen that Canada is the only country that has played an overall positive role (2.1%) in advancing the G7's GDP growth for the period of 2000−2020, while other countries all showed negative roles with Italy being the worst. In comparison, all G7 countries have played positive roles in lowering the unemployment rate, with Germany ranking at the top (8.3%) and Canada at the bottom (2.2%). It is clear that all G7 countries have generally contributed negatively to increasing the manufacturing value added as a proportion of GDP and per capita due to the shift of manufacturing industries to China and other Southeast Asia countries. As for the death rate from natural disasters, Canada, Germany, and Japan have played negative roles in safeguarding the local communities. These negative contributions might be linked to: (1) the increase of unprecedented natural disasters and climate extreme events in recent years, and (2) the lack of natural hazard mitigation policies and emergency management measures. The G7 countries also presented inconsistent performances in the protection of marine resources and freshwater biodiversity. For instance, Japan, France, and the UK have shown overall positive roles in protecting marine resources while the other countries contributed negatively with the US and Germany being the worst; in comparison, France and Italy are the only two countries showing overall positive roles in protecting the freshwater biodiversity.

To evaluate the G7's overall contributions to the two groups of SDG indicators (i.e., economic and environmental), here we rank the seven member countries by further calculating the median of all median synergy contributions presented in Fig. 5 and Supplementary Figs S7-S12. The ranking results are shown in Fig. 6. For economic SDG indicators, all member countries have played positive roles in advancing the G7 economies over the period of 2000-2020. This demonstrates a clear alignment with one of its primary goals which is to promote economic development. In particular, Japan and Canada rank at the top 2 countries (almost tied up with a positive contribution of 7.90%), followed by the US with a positive contribution of 6.69%; Italy ranks at the bottom with a positive contribution of 4.60%, while Germany, the UK, and France rank at the 4th, 5th, and 6th places. In comparison to the binding collaboration in economic indicators, the G7 countries exhibit uncooperative performances in addressing the environmental SDG indicators. In detail, the well-ranked countries in economic indicators (i.e., Japan, Canada, the US, Germany, and the UK)

Fig. 5 | Synergy contributions from G7 member countries for six selected SDG indicators. a SDG 8.1.1, (**b**) SDG 8.5.2(1), (**c**) SDG 9.2.1, (**d**) SDG 13.1.1(1), (**e**) SDG 14.1.1(1), and (**f**) SDG 15.1.2(1). Cells with green background color indicate positive contributions while cells with orange background color signify negative contributions. Cells filled with gray background color are used to reflect two situations: (1) no data are available for this year, or (2) no synergy is calculated for this year. Note that the median contributions presented at the bottom of each plot only reflect the general roles of individual countries in each SDG indicator over the period of 2000-2020. These median contributions do not necessarily add up to +100% or −100%.

are poorly ranked for environmental indicators with either negative contributions (−8.84% for Canada, −6.27% for Germany, and −2.66% for the US) or a very small positive contribution (0.12% for Japan and 0.55% for the UK); by contrast, France and Italy are ranking at the 1st and 2nd places with positive contributions of 6.27% and 6.24%, respectively. The good performances of France and Italy in conserving the environment are largely due to their proactive policies for enhancing environmental sustainability[35,36]. The reason that Canada ranks at the bottom for environmental indicators is mostly because the country has been slow to implement climate change commitments, such as carbon pricing and emission regulations[37]. The G7's discrepancies in environmental indicators further emphasize that all member countries need to

strengthen their collaboration to tackle climate change and preserve the planet's biodiversity in order to achieve the environmental SDGs.

Discussion
Extensive cooperation and synchronized policymaking are critical components in reaching the Sustainable Development Goals of the Agenda 2030. This paper proposes a new methodological framework that quantitatively measures the amount of synergy among a group of countries based on the SDG indicators. The proposed framework entails three primary components: (i) a quantitative assessment of the oscillation in SDG indicators caused by both domestic and foreign changes, (ii) a determination of the gross synergy in SDG indicators to
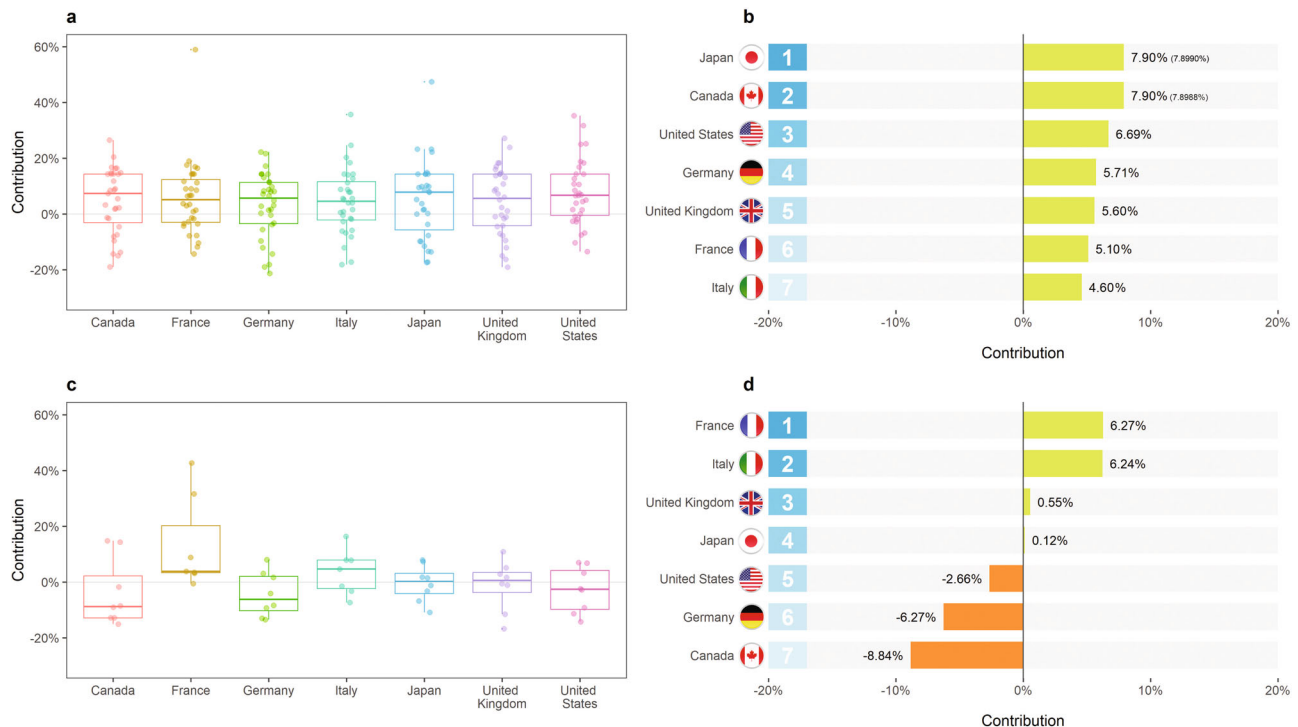
Fig. 6 | G7's overall roles in advancing the economic and environmental SDG indicators. a and **c** show the boxplots of median synergy contributions by individual countries to all economic SDG indicators and all environmental SDG indicators, respectively; **b** and **d** show the ranking of G7's overall roles in advancing the economic and environmental SDG indicators, respectively. Note that the percentage contributions shown in **b** or **d** do not necessarily add up to 100% or −100%.

evaluate the cooperation or competition among all countries, and (iii) a separation of the contributions from individual countries to the advancement of SDGs. The framework is applied for the G7 countries to provide a quantitative assessment of their collaborative efforts in promoting the SDGs over the period of 2000–2020. The results suggest that the G7 countries have all contributed positively to economic SDG indicators, while significant discrepancies in environmental SDG indicators are reported. This highlights the need for further collaboration among G7 countries to tackle emerging environmental issues, such as climate change and shrinking biodiversity. While the results from this study identify the existing strengths and challenges in both economic and environmental SDGs among the G7 countries, it is noteworthy to mention that the socio-dimensional aspects of SDGs are not evaluated here due to the lack of quantitative data in the related SDG indicators.

Economic policy recommendations

Our analysis of the overall synergy of G7 countries for economic SDG indicates that all seven countries have contributed positively to the G7's collective economic progress. These positive contributions suggest a degree of cooperation and mutual reinforcement among these nations, reflecting a successful alignment of policies and strategies toward economic development and sustainability. Given this positive synergy, the general recommendation is that the G7 countries maintain their current economic policies since they have worked effectively to enhance economic outcomes. However, it is essential to emphasize that this general recommendation is only based on the pre-COVID-19 pandemic conditions as our analysis here only covers data until 2020 due to the delay in reporting and updating SDG data; the widespread impacts of COVID-19 pandemic on G7's economies are not fully reflected. There is no doubt that the COVID-19 pandemic has disrupted economies and economic structures globally, necessitating re-evaluating and adapting policies to restore and exceed pre-pandemic levels of economic synergy. Therefore, it is prudent that

G7 countries implement radical or aggressive policies that address immediate economic recovery. These policies should address the unprecedented economic disruptions caused by the pandemic and foster resilience and sustainable growth. For example, governments should introduce large-scale fiscal stimulus packages to revitalize economic activities. These packages should focus on infrastructure development, digital transformation, and green energy projects[38] to stimulate job creation and economic growth. Investments in these areas not only drive immediate economic recovery but also contribute to long-term sustainability and resilience, addressing SDGs related to industry, innovation, and infrastructure (SDG 9), affordable and clean energy (SDG 7), and decent work and economic growth (SDG 8). Governments should also consider substantial investments in healthcare infrastructure and pandemic preparedness to ensure resilience and long-term sustainability (SDG 3), including expanding healthcare capacities[39], securing a steady supply of medical resources[40], and developing comprehensive plans and policies for future pandemics and catastrophic events. Additionally, governments should plan and construct policies for preparedness to undertake urgent measures for vaccine creation and providing treatments, which are crucial for a proactive healthcare strategy. These measures ensure that health systems are robust and capable of withstanding future crises, thereby safeguarding public health and well-being. Targeted financial strategies, such as access to low-interest loans, grants, and tax and carbon tax relief support and incentives[41,42], can help small and medium enterprises (SMEs), which are the backbone of economies but were severely affected by the pandemic, to recover and thrive and help boost economic growth (SDG 8). Furthermore, accelerating the digitalization of economies through investments in digital infrastructure and the promotion of digital literacy[43], such as support for remote work, online education, and digital commerce which can help reduce employment and education costs, increase accessibility, and stimulate economic growth in the post-pandemic era (SDG 4 and SDG 9)

Environmental policy recommendations

Our analysis of G7's overall synergy in environmental SDG indicators suggests that the G7 countries must further strengthen their collaboration in addressing emerging environmental issues, such as climate change and biodiversity loss. For those countries with negative or small positive contributions to the overall synergy in environmental SDG indicators (e.g., Canada, Germany, US, Japan, and UK), it is important to develop programs for conserving mountain ecosystems and biodiversity, focusing on protected areas and wildlife corridors in mountainous regions and implementing a National Biodiversity Action Plan, like Australia[44], focusing on mountainous regions, including measures such as establishing new protected areas, implementing species recovery plans, investing in habitat restoration and conservation, and promoting sustainable land management practices[45,46]. Internationally, the G7 countries can leverage their collective resources, expertise, and political influence through concerted efforts to address common environmental challenges and achieve shared goals. Our key recommendations include establishing platforms for information sharing and best practices exchange, conducting joint research and monitoring programs, aligning policies for achievable goals, providing capacity building and technical assistance, mobilizing financial support and investment, launching collaborative conservation initiatives targeting transboundary ecosystems, and coordinating public awareness and outreach campaigns. Furthermore, private companies and non-government organizations can collaborate with their respective governments by investing in conservation initiatives, implementing sustainable environmental, social, and governance (ESG) practices, and engaging in corporate social responsibility (CSR) activities[47,48]. This will help promote sustainable trade and supply chain management practices[49], reduce the environmental footprint of their operations, and support initiatives that empower local communities[50].

Methods

Data Collection

A total of 42 SDG indicators for economic and environmental dimensions are derived from the *Our World in Data* database[51] for the period of 2000–2020. These indicators are selected with consideration of the major global events, such as financial disasters (e.g., the stock market crash in 2007–2009), international agreements (the Paris Agreement in 2015), the COVID-19 pandemic started in 2020. This is to ensure that the SDG synergy among the G7 countries under global instability and crisis can be analyzed and quantified. Due to their unit differences, all SDG indicators are normalized as follows:

$$x_t = \frac{x\prime_t - \min(X)}{\max(X) - \min(X)} \quad (1)$$

where, x_t is a unitless normalized indicator varying between 0 and 1 with a yearly time step denoted as $t(t = 1, 2, \ldots, T)$. Here T represents the total number of years. $x\prime$ represents the actual indicator value; $\min(X)$ and $\max(X)$ are the minimum and maximum indicator values among all years, respectively.

The detailed definitions of these 42 SDG indicators and their expected directions are presented in Table 1. In particular, here we use two signs: − (decreasing) and + (increasing), to represent the expected directions for all SDG indicators considered in this study. Note that the situation for "no-change" is not considered here. This is because all the selected SDG indicators are expected to change over time to achieve long-term sustainability.

Oscillation in SDG Indicators

The oscillation in SDG indicators is typically caused by major international and/or domestic events (such as political elections and financial crises)[52]. It is important to quantify the oscillation of SDG indicators in order to comprehend the synergy among a group of countries. In this study, the oscillation in SDG indicators is separated into two types of changes: Domestic Changes (denoted as *DC*) and Foreign Changes (denoted as *FC*), with the purpose of reflecting the compound impacts of domestic and international events.

The *DC* for each SDG indicator over a period of T years is defined as a vector of all distances among the indicator values over any two successive years. In particular, for a specific country j, the distance of each SDG indicator from year t to year t + 1 is expressed as d^j_t and can be calculated as follows:

$$d^j_t = \sqrt{\left(x^j_{t+1} - x^j_t\right)^2} \quad (2)$$

Since all SDG indicators are normalized to the range of [0, 1], the value of d^j_t also varies in the range of [0, 1]. In details, a distance of 0 indicates no domestic change; a distance of 1 measures either the largest jump (i.e., where x^j_{t+1} is the maximum and x^j_t is minimum over the entire period of T) or the largest drop (i.e., where x^j_{t+1} is the minimum and x^j_t is maximum over the entire period of T). The domestic change for country j over the entire period of T can thus be expressed as follows:

$$\boldsymbol{DC^j} = (d^j_1, d^j_2, \ldots, d^j_{T-1}) \quad (3)$$

While *DC* is used to measure the domestic change for a specific country, the *FC* is introduced to measure the compounded changes for a group of countries. Similar to *DC*, the *FC* for each SDG indicator is defined as a vector of distances. However, the distance used for *FC* will be calculated for all countries in the group (rather than an individual country). Assume that the total number of countries to be considered in a group is denoted J, then the *FC* distance for each SDG indicator from year t to year t + 1 is expressed as d_t and can be calculated as follows:

$$d_t = \sqrt{\sum_{j=1}^{J} \left(x^j_{t+1} - x^j_t\right)^2} \quad (4)$$

Here, the values of d_t typically vary in the range of $[0, \sqrt{J}]$. A distance of 0 indicates no foreign change, which implies that all countries in a group have either reached their SDG goal or decided to make no improvement all together. A distance of $\sqrt{J}$ means all countries have experienced the largest jumps/drops at the same time. The synchronization of sudden changes is typically observed among some countries that have similar interests, governmental structures, and good relations on the international stage. Similarly, the foreign change for a group of countries over the entire period of T can thus be expressed as follows:

$$\boldsymbol{FC} = (d_1, d_2, \ldots, d_{T-1}) \quad (5)$$

Synergy in SDG Indicators

The synergy among a group of countries for individual SDG indicators can be quantified by considering both the domestic changes for individual countries (i.e., *DC*) and the foreign changes within a group of countries (i.e., *FC*). This is because all member countries will be influenced by both foreign relations and domestic discrepancies. The synergy for a group of countries is defined as the sum of the domestic changes of individual countries subtracted by their foreign changes. Specifically, the synergy for year t for a total of J countries is expressed

as s_t and can be calculated as follows:

$$s_t = \frac{1}{J}\left(\sum_{j=1}^{J} d_t^j - d_t\right) = \frac{1}{J}\left(\sum_{j=1}^{J}\sqrt{\left(x_{t+1}^j - x_t^j\right)^2}\right) - \frac{1}{J}\left(\sqrt{\sum_{j=1}^{J}\left(x_{t+1}^j - x_t^j\right)^2}\right)$$

(6)

Here the division by J (i.e., the total number of countries) ensures that the range of synergy stays within the range of [0, 1]. A synergy of zero indicates no change in an SDG indicator has been observed from year t to year $t+1$ for this group of countries. This typically takes place in two situations: (1) all member countries have made no progress at all in the SDG indicator, or (2) some countries have made positive changes while other countries have made negative changes in the SDG indicator, resulting in an exact offset between domestic changes and foreign changes. Thus, a synergy close to zero indicates that all member countries have been refusing to work together or competing with one another. In comparison, a synergy close to one would be obtained when the sum of DC for J countries is strictly larger than their FC. This means that all member countries have been working together to change the SDG indicator. The synergy among all member countries for the entire period of T can be similarly represented by a vector, as follows:

$$\boldsymbol{S} = \frac{1}{J}\left(\sum_{j=1}^{J}\boldsymbol{DC^j} - \boldsymbol{FC}\right) = (s_1, s_2, \ldots, s_{T-1})$$

(7)

Here we should note that the synergy concept introduced so far can only be used to quantify whether all member countries are collaborating or competing with one another. However, it is incapable of

reflecting whether they are collaboration/competing to improve the SDG indicator along with its expected direction or deteriorate it towards the opposite direction. To address this issue, here we further introduce the direction of synergy based on the gradient of change over two consecutive years, which is expressed as follows:

$$g_t = \frac{1}{J}\sum_{j=1}^{J}\left(x_{t+1}^j - x_t^j\right)$$

(8)

To define the direction of change, we introduce the following sign function:

$$\text{sgn}(g_t) = \begin{cases} +1 \text{ if } g_t > 0 \\ -1 \text{ if } g_t < 0 \end{cases}$$

(9)

The output from the above sign function is then compared to the expected direction of the SDG indicator to determine the sign of synergy, as follows:

$$\text{sgn}(s_t) = \begin{cases} +1 & \text{if } \text{sgn}(g_t) = \text{the expected SDG direction} \\ -1 & \text{otherwise} \end{cases}$$

(10)

A positive sign for synergy indicates that the member countries are improving the SDG indicator together along with its expected direction (shown in Table 1), while a negative sign implies a collective movement towards the opposite direction.

In addition to gross synergy, it is also important to further measure the contributions of individual countries to the gross synergy to better understand their roles in the group. Here, we use c_t^j to indicate the contribution from country j to the gross synergy from year t to year
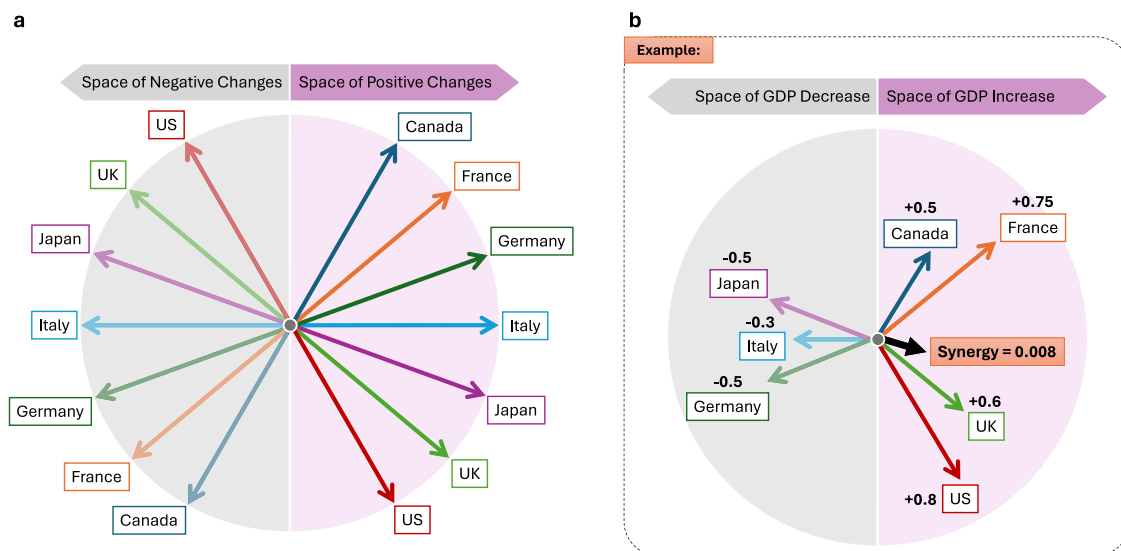
a

b

Fig. 7 | An illustration of gross synergy and synergy contributions from individual countries. a a general illustration of G7's changes in SDG indicators. For a specific SDG indicator, the change of each country can be either positive (matching the expected direction of this SDG indicator) or negative (moving towards the opposite direction of the SDG indicator). The space is split into two parts to represent both positive and negative changes from member countries. The change of each country can be represented by an arrowed line with the arrow pointing towards one of the two spaces to represent either a positive or negative change. The magnitude of the change can be represented by the length of the line. **b:** an illustrative example for the SDG indicator for GDP growth. The expected direction of GDP growth is to "increase GDP", therefore all member countries are hoping to make changes towards to the space of GDP increase. In this example, four countries (including Canada, France, UK, and US) manifest positive changes (i.e., increases in GDP) while the remaining three countries (including Japan, Italy, and

Germany) show negative changes (i.e., decreases in GDP). The gross synergy for the G7 countries is positive, indicating that the majority of member countries (i.e., Canada, France, UK, and the US) are moving towards the expected direction (i.e., GDP growth), and thus these countries are contributing positively to the gross synergy. However, the magnitude of synergy is small because some member countries (i.e., Japan, Italy, and Germany) are moving in the opposite direction and they are contributing negatively to the gross synergy. Therefore, the policy implication here is that the countries with negative contributions should adjust their policies to increase collaboration with other member countries in order to achieve the goal for GDP growth. Note that the numeric values displayed in the example are not true data and only for illustrative purposes. The detailed contributions from individual countries can be calculated with Eq. (11), which also requires the calculation of foreign changes by Eq. (4).
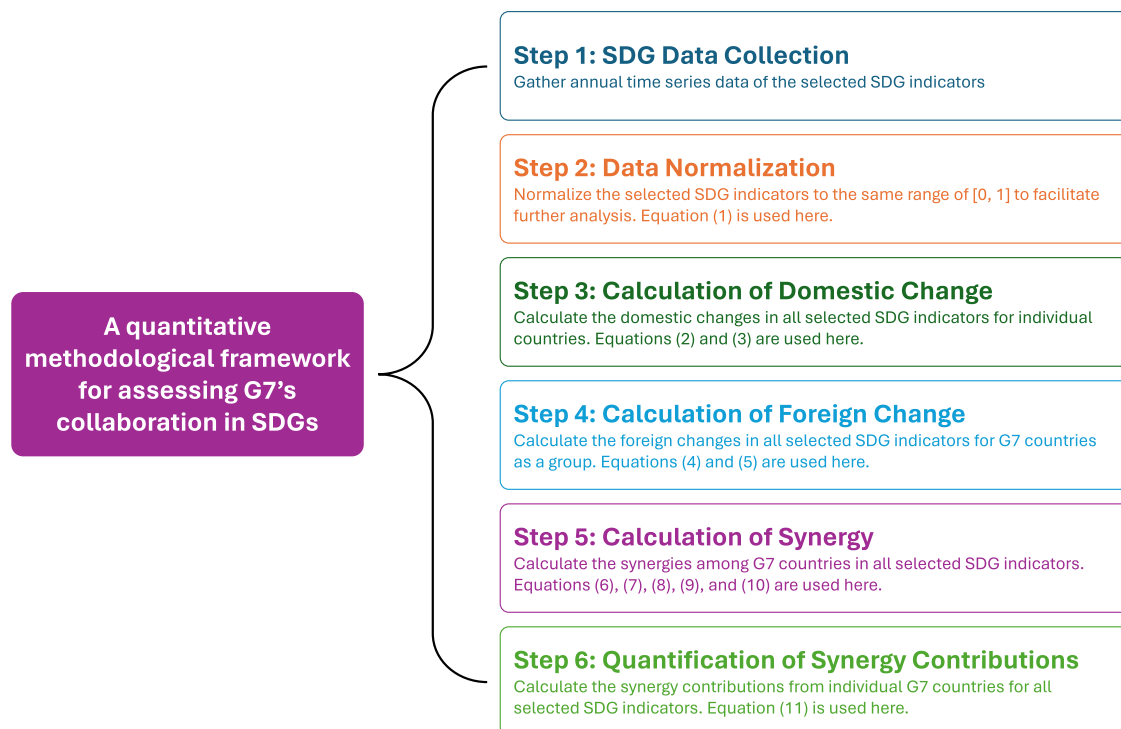
Step 1: SDG Data Collection
Gather annual time series data of the selected SDG indicators

Step 2: Data Normalization
Normalize the selected SDG indicators to the same range of [0, 1] to facilitate further analysis. Equation (1) is used here.

Step 3: Calculation of Domestic Change
Calculate the domestic changes in all selected SDG indicators for individual countries. Equations (2) and (3) are used here.

Step 4: Calculation of Foreign Change
Calculate the foreign changes in all selected SDG indicators for G7 countries as a group. Equations (4) and (5) are used here.

Step 5: Calculation of Synergy
Calculate the synergies among G7 countries in all selected SDG indicators. Equations (6), (7), (8), (9), and (10) are used here.

Step 6: Quantification of Synergy Contributions
Calculate the synergy contributions from individual G7 countries for all selected SDG indicators. Equation (11) is used here.

A quantitative methodological framework for assessing G7's collaboration in SDGs

Fig. 8 | A methodological framework for quantitatively assessing G7's collaboration efforts in SDGs. This framework consists of six key steps, including data collection, data normalization, calculation of demestic change, calculation of foreign change, calculation of synergy, and quantification of synergy contributions. The equation(s) needed for each step are specified in the figure.

$t+1$, and it can be calculated as follows:

$$c_t^j = \frac{d_t^j - \frac{d_t}{J}}{s_t \times \mathrm{sgn}(s_t) \times J} \times 100\% \tag{11}$$

where the sign of c_t^j indicates whether country j is contributing positively or negatively to the group synergy. Note that the synergy contribution of an individual country for a specific indicator can go beyond the range of -100% to +100%; however, the sum of contributions from all countries for this indicator should always be equal to 100% (for positive gross synergy) or -100% (for negative gross synergy).

Figure 7 provides a visual illustration of the concept of overall synergy and synergy contributions from individual countries. Overall, the methodological framework used to quantitatively assess G7 countries' collaboration in SDG indicators can be summarized into six key steps (shown in Fig. 8), including (1) SDG data collection, (2) data normalization, (3) calculation of domestic changes, (4) calculation of foreign changes, (5) calculation of synergy, and (6) quantification of synergy contributions.

Data availability
The data for the 42 SDG indicators over the period of 2000-2020 used in this study are obtained from the Our World in Data database (website: https://ourworldindata.org). The data can also be downloaded at: https://doi.org/10.5281/zenodo.11659806.

Code availability
R programming language is used in this project to handle data processing, synergy calculation, and figure generation. All the R source codes are available at: https://doi.org/10.5281/zenodo.11659806.

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Author contributions

K.L. and X.W. conceived of the presented idea. K.L., A.R. and X.W. developed the theory. A.R. and Q.V.D. performed the computations. X.W. and Q.V.D. verified the analytical methods. X.W. supervised the project and took the lead in writing the manuscript. All authors contributed to the writing of the initial manuscript, provided critical feedback, and helped shape the final manuscript.

Competing interests

The authors declare no competing interest.

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