nature sustainability

ANALYSIS

https://doi.org/10.1038/s41893-020-0572-z

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Impacts of international trade on global sustainable development

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The United Nations has adopted 17 Sustainable Development Goals (SDGs) with 169 targets. International trade has substantial influences on global sustainability and human well-being. However, little is known about the impacts of international trade on progress towards achieving the SDG targets. Here we show that international trade positively affected global progress towards achieving nine environment-related SDG targets. International trade improved the SDG target scores of most (65%) of the evaluated developed countries but reduced the SDG target scores of over 60% of the evaluated developing countries. The SDG target scores of developed countries were higher than those of developing countries when trade was accounted for, but those scores would be lower than those of developing countries if trade were not a factor. Furthermore, trade between distant countries contributed more to achieving these global SDG targets than trade between adjacent countries. Compared with adjacent trade, distant trade was more beneficial for achieving SDG targets in developed countries, but it more negatively affected SDG target scores in developing countries. Our research suggests that enhancing the accounting for and management of virtual resources embedded in trade is essential for achieving and balancing sustainable development for all.

The United Nations adopted the 17 Sustainable Development Goals (SDGs) in 2015 to help achieve global sustainable development through environmental conservation, economic development and social inclusion[1]. To date, 193 nations have committed to these ambitious goals with 169 targets. International trade plays an increasingly important role in alleviating regional resource scarcity, facilitating efficient global resource consumption[2], stimulating economic growth and improving social welfare[3] because transferring goods and services can help not only meet the regional demand but also conserve local resources that are essential for commodity production[4]. However, international trade can also negatively impact environmental and social well-being by, for instance, contributing to carbon leakage (that is, CO_2 emission displacement)[5], biodiversity loss[6] and deforestation[7,8], and by exacerbating environmental and socio-economic inequality between developed and developing countries[9].

Despite the far-reaching implications of international trade and the substantial literature examining its impacts on the economy and sustainability[10–13], an assessment of its impacts on global progress towards achieving the SDG targets is lacking. Previous research has focused on the impacts of international trade on a single aspect of sustainable development, such as CO_2 emissions[13], deforestation[7,14] or health[15]. But there is little research quantitatively assessing multiple aspects of sustainable development simultaneously at the global scale over time. In particular, given the arguments that trade can have different impacts on developed and developing countries, it is important to assess such differences to inform international trade agreements. Furthermore, there is no research comparing the impacts of international trade between adjacent countries[16,17] (countries sharing land or maritime boundaries) and between distant countries[16,17] (countries that do not share land or maritime boundaries) on progress towards SDG targets. Such information is urgently required since international trade is rapidly expanding worldwide, and various kinds of virtual resource flows (for example, virtual water, energy, materials and land) embedded in trade commodities and the accompanying displacement of environmental burdens (for example, CO_2 emissions) can substantially influence progress towards achieving SDG targets in trading countries. Quantifying the different impacts of international trade on sustainable development between developed and developing countries can inform efforts to enhance equity. Moreover, comparing the impacts from adjacent and distant countries can help uncover unexpected socio-economic and environmental interactions between different types of countries that shape global sustainability[18,19]. These insights can provide valuable information for global efforts to achieve SDG targets across spatial scales.

To fill these knowledge gaps, we assessed the impacts of international trade on nine environment-related SDG targets that are likely to be affected by trade and for which there are available data and clear quantitative metrics: SDG 6.4 (ensure sustainable water withdrawals and supply), SDG 7.2 (increase substantially the share of renewable energy in the global energy mix), SDG 7.3 (improve energy efficiency), SDG 8.4 (improve resource efficiency in consumption and production), SDG 9.4 (promote clean and sustainable industrialization), SDG 12.2 (achieve sustainable management and efficient use of natural resources), SDG 13.2 (integrate climate change measures into national policies, strategies and planning), SDG 15.1 (ensure sustainable use of terrestrial ecosystems) and

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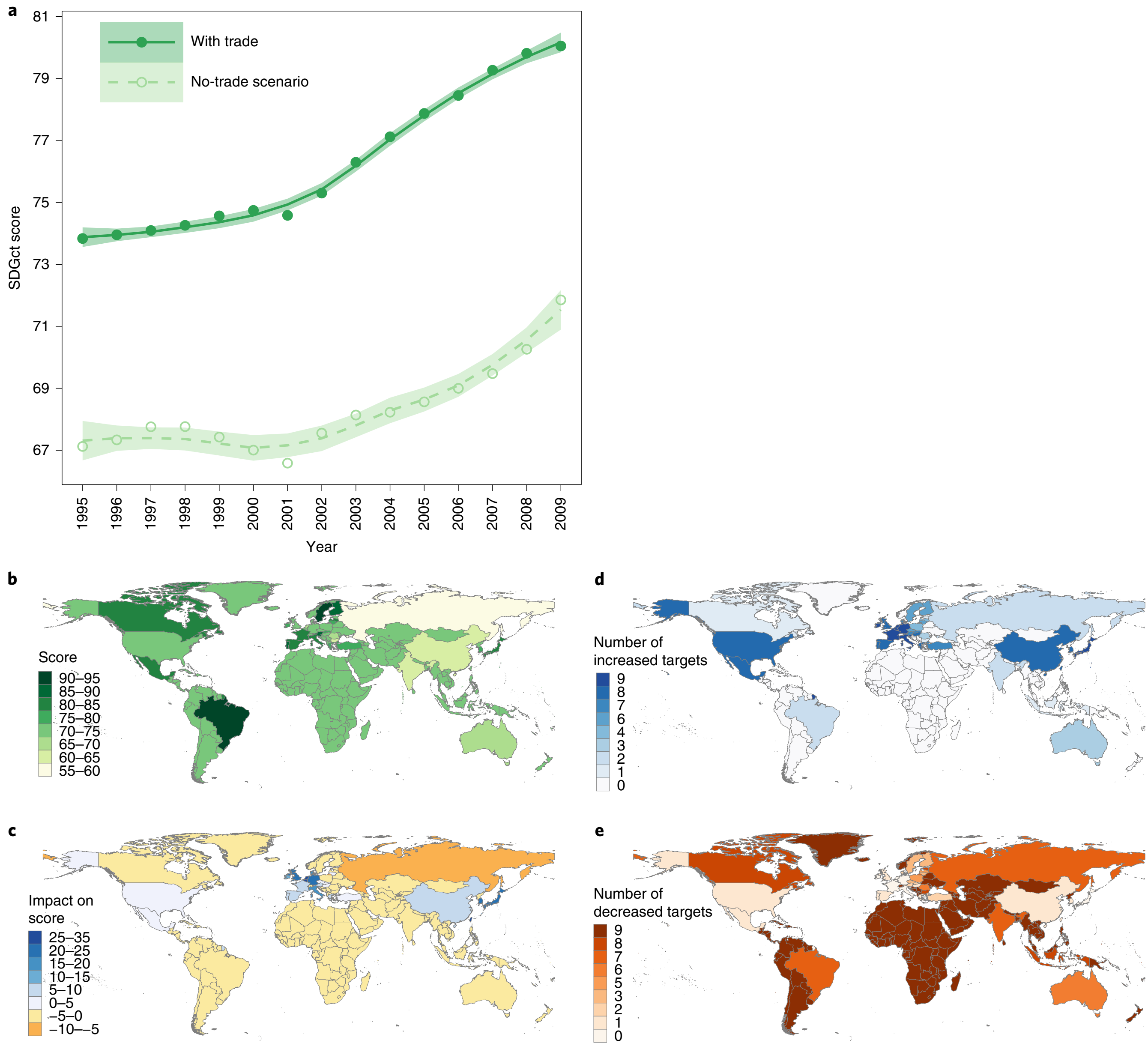

Fig. 1 | The temporal change and spatial pattern of SDG target scores. a, Temporal change in SDGct scores at the global level. The solid dots represent the SDGct scores of the real world with international trade, and the hollow dots represent scores in a hypothetical no-trade world scenario. The shading indicates the 95% confidence intervals for predictions from a smooth local regression model using R v.3.4.4 (ref. [60]). **b**, Actual SDGct scores for all countries. The scores were calculated from the average value of the SDGct scores in each country from 1995 to 2009. **c**, The average impacts of trade on SDGct score changes. The values were calculated from the average difference in SDGct scores between the trade and no-trade scenarios at the national level from 1995 to 2009. **d**,**e**, Number of SDG targets with increased (**d**) or decreased (**e**) scores due to international trade for each country.

SDG 15.2 (promote sustainable forest management). We selected and studied these SDG targets because they have measurable indicators for assessing the impacts of trade. We acknowledge that trade may have impacts on other SDG targets, but due to the data availability, we first use these nine measurable targets to illustrate a quantitative approach (see more details in the Methods and Discussion). We addressed the following questions. First, what are the spatial–temporal dynamics of progress towards achieving multiple SDG targets at the global and national levels? Second, what are the impacts of international trade on progress towards achieving these SDG targets at the global and national levels, and how have these impacts changed over time? Third, how do the impacts of international trade differ between developing countries and developed countries? Fourth, how do the impacts of trade between distant countries differ from those between adjacent countries? To address these questions, we assessed each country's performance in achieving the SDG targets, measured in terms of SDG target scores under the current global trade system and under a hypothetical no-trade scenario (that is, without accounting for trade; see Methods). Comparing SDG target progress between trade and no-trade scenarios can help estimate the impacts of international trade on sustainable development. We then compared the different impacts of international trade on the SDG target scores between developed and developing countries, and compared impacts from adjacent and distant trade. This study applied the framework of metacoupling[20] (socio-economic–environmental interactions within as well as between adjacent and distant places) to identify human–nature interactions (for example, trade) across different spatial scales.

Results

Global trend and spatial pattern of progress towards multiple SDG targets. Overall, the scores of the evaluated SDG targets have increased since 1995. The composite SDG target score (SDGct, representing the overall performance in achieving all evaluated SDG targets; see detailed information in the Methods) of countries worldwide increased 8%, from approximately 74 (s.d. = 10.4) in 1995 to approximately 80 (s.d. = 6.8) in 2009 (Fig. 1a). The sharpest and steadiest increase in the SDGct score occurred after 2001, with the global SDGct score increasing at a rate of approximately one score unit per year. Most European countries (for example, Sweden, Finland, Austria, Slovenia, Portugal, Latvia, Luxembourg, Spain and France), Brazil, Mexico, Canada and Japan scored relatively high in sustainable development (score > 80), while Russia, China, India, Bulgaria, Malta, Romania, the Netherlands and Australia scored lower than 70 (Fig. 1b and Supplementary Fig. 1; and see the country list in the Methods and Supplementary Table 1).

Impacts of trade on SDG targets across global to national levels. Compared with the no-trade scenario, international trade improved the global SDGct score and positively affected progress towards achieving all nine SDG targets at the global level (Fig. 2). The impacts of trade generally increased from 1995 to 2009 (Fig. 1a and Supplementary Figs. 2 and 3). However, international trade had different impacts across countries. Most European countries, Japan, South Korea, China, the United States and Mexico were the main beneficiaries of international trade in terms of increasing their respective SDGct scores (Fig. 1c). Among them, most European countries, Japan, South Korea, China, the United States and Mexico experienced improvements in at least eight SDG target scores from international trade. However, not all countries experienced increases in their SDGct scores from international trade. International trade led to decreases in SDGct scores in Indonesia, Estonia, Canada, Bulgaria, India, Brazil, Russia and the rest of the world (Fig. 1c). These decreases occurred in at least seven out of the nine evaluated SDG targets (Fig. 1d,e and Supplementary Fig. 4).

Impacts of trade on SDG targets between developed and developing countries. The disparity in SDGct scores between developed and developing countries was much larger when accounting for trade than when not accounting for trade (Fig. 2a,b). With international trade, progress towards achieving the SDG targets improved in most developed countries but declined in most developing countries (Fig. 2c). Over 65% of developed countries had increases in all nine SDG target scores under international trade, while more than 60% of developing countries experienced declines in most of the evaluated SDG targets under international trade (Fig. 2c and Supplementary Fig. 4). Among the nine SDG targets, international trade had the largest positive impacts on progress towards achieving SDGs 15.1 and 15.2 (ensure sustainable use of terrestrial ecosystems and promote sustainable forest management) for developed countries, followed by SDGs 8.4 and 12.2 (improve resource efficiency in consumption and production, and achieve sustainable management and efficient use of natural resources) (Fig. 2d). For developing countries, international trade had the largest negative impacts

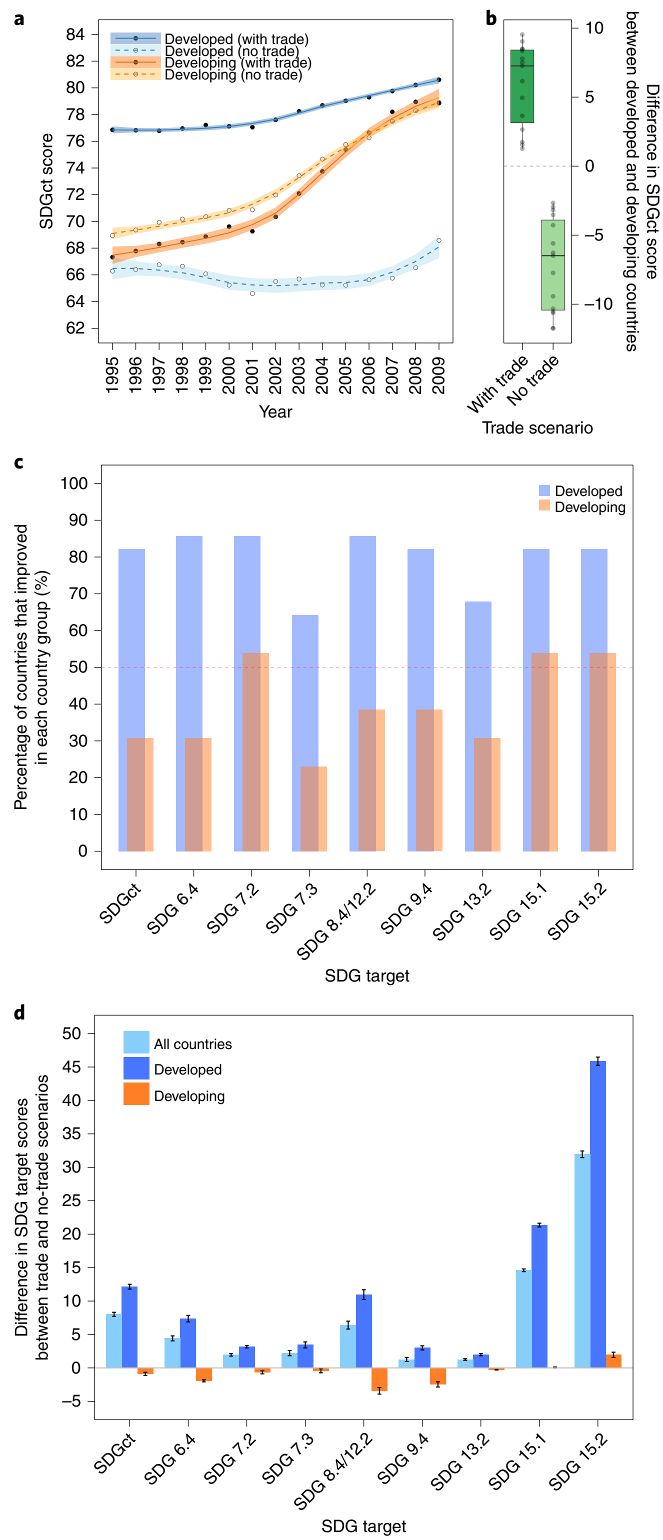

Fig. 2 | Impacts of international trade on SDG targets differed between developed and developing countries. a, The temporal change in SDGct scores for developed and developing countries under the trade and no-trade scenarios. **b**, The differences in SDG target scores between developed countries and developing countries over 15 years under the trade and no-trade scenarios. In each box plot, the central rectangle box spans the first quartile (Q1) to the third quartile (Q3). The centre line segment inside the rectangle represents the median value. The upper whisker is the maximum value while the lower whisker is the minimum, and the dots represent each data point. **c**, The percentages of countries that improved in each SDG target score. The red horizontal dashed line stands for 50%. **d**, Differences in SDG target scores between trade and no-trade scenarios. Positive values indicate positive impacts of trade on achieving the SDG targets. The error bars indicate the standard errors in the SDG target scores ($n = 15$).

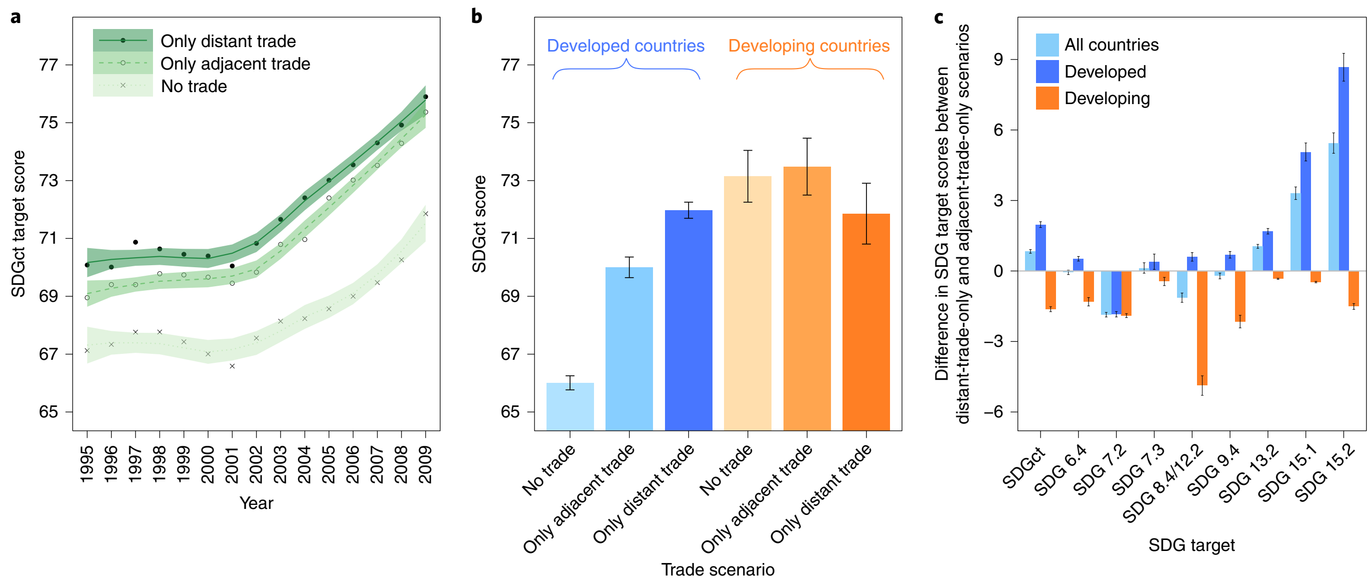

Fig. 3 | Comparison of SDG target scores between a distant-trade scenario and an adjacent-trade scenario. a, The temporal change in SDGct scores for all countries under three trade scenarios. **b**, SDGct scores for developed and developing countries under each trade scenario. **c**, Differences in SDG target scores between the two trade scenarios (calculated by $SDG_{distant}$ minus $SDG_{adjacent.}$). The error bars indicate the standard errors in the SDG target scores ($n = 15$).

on progress towards achieving SDGs 8.4 and 12.2, followed by SDG 9.4 (promote clean and sustainable industrialization) and SDG 6.4 (ensure sustainable water withdrawals and supply).

The SDG target scores of developed countries were higher than those of developing countries with international trade, but they would be surprisingly lower than those of developing countries without trade (Fig. 2a). International trade improved developed countries' sustainable development levels, while it reduced the sustainable development levels of developing countries from 1995 to 2005. It is interesting that from 2006 to 2009, international trade began to generate positive impacts on developing countries' SDG target scores. Without trade, the SDGct scores of developed countries would be even lower than those of developing countries from 1995 to 2009. However, with international trade, the SDGct scores of developed countries steadily increased from 1995 to 2009 and were consistently greater than those of developing countries (Fig. 2a).

Impacts of distant trade versus adjacent trade. On average, distant trade contributed more towards achieving the evaluated SDG targets than did adjacent trade (Fig. 3a). Interestingly, the impacts of distant and adjacent trade differed between developed countries and developing countries (Fig. 3b). Developed countries experienced larger improvements from distant trade than from adjacent trade, while developing countries suffered from greater reductions in SDG target scores from distant trade than from adjacent trade (Fig. 3c).

Discussion

This study presents a quantitative assessment of the impacts of international trade on progress towards achieving global SDG targets. Most existing studies have assessed countries' sustainable development relative to internal drivers[21,22] (for example, national development policies, management strategies for natural resources, technological advances and shifts in ideology) rather than external drivers such as international trade[23–26]. But at least since Adam Smith's *Wealth of Nations*, there has been debate about the effects of trade on human well-being and the environment, so looking at the effects of trade seems a logical place to begin examinations of how external factors influence a country's sustainable development. Our results show that international trade improved global progress towards achieving nine environment-related SDG targets, indicating that trade between countries can help facilitate global sustainable development. Because of the comparative advantage, international trade often encourages optimized allocation of natural resources around the world, improves efficiency in resource use and promotes sustainable economic growth[27–29].

However, as often argued by critics of trade, the overall average improvement masks differences in the impacts of trade across countries[10,30]. We find that developed countries benefited from trade in term of progress towards all nine evaluated SDG targets, while developing countries' progress was degraded in most of the targets (except a small increase in SDG 15.2—promote sustainable forest management). Although globalization can bolster the economies of developing countries (for example, China increased its gross domestic product (GDP) 1,500-fold from 1995 to 2016; ref. [31]), there are also negative environmental impacts associated with international trade, such as CO_2 emissions leakage and land-use displacement[32]. Developed countries usually gain environmental benefits (for example, increases in SDG target scores) at the cost of developing countries, and developing countries often bear most of the environmental burdens of resource extraction[29]. For example, international trade displaced 16 Gt of CO_2 from developed countries to developing countries from 1990 to 2008 (ref. [33]), which largely stabilized the CO_2 emissions in developed countries but doubled the CO_2 emissions in developing countries[34–36]. This is partly because stringent regulations in developed countries tend to displace pollution-intensive industries to developing countries with lax environmental standards and cheap resources and labour.

Our results also indicate that distant trade has larger positive impacts on progress towards achieving SDG targets than adjacent trade. This is partially because countries have more distant trade partners than adjacent ones (on average); thus, there were more trade interactions between distant countries than between adjacent countries. In addition, adjacent countries usually have similar socio-economic and environmental conditions, which determine

Table 1 | SDG indicators under with-trade and no-trade scenarios

No.	SDG targets	SDG indicators illustration	SDG indicator score under trade scenario	SDG indicator score under no-trade scenario
1	6.4 Ensure sustainable water withdrawals and supply	6.4.1 Change in water-use (WU) efficiency over time	$S = f\left(\frac{GDP}{WU}\right)$ *S*, score for the indicator. GDP is in US dollars (constant 2011 international dollars). WU is in cubic metres.	$S^* = f\left(\frac{GDP-NE}{WU-NEVW}\right)$ NE, net exports measured in US dollars (calculated from WIOD tables[58]). NEVW, net exported virtual water embedded in international trade.
		6.4.2 Level of water stress: freshwater consumption as a proportion of available freshwater resources (WR)	$S = f\left(\frac{WU}{WR}\right)$	$S^* = f\left(\frac{WU-NEVW}{WR}\right)$
2	7.2 Increase substantially the share of renewable energy in the global energy mix	7.2.1 Renewable energy share in the total final energy consumption	$S = f\left(\frac{REU}{TEU}\right)$ REU, renewable energy use. TEU, total energy use.	$S^* = f\left(\frac{REU-NEVREU}{TEU-NETVEU}\right)$ NEVREU, net exported virtual renewable energy use embedded in international trade. NETVEU, net exported virtual energy use embedded in international trade.
3	7.3 Improve energy efficiency	7.3.1 Energy intensity measured in terms of primary energy and GDP (low energy intensity indicates high SDG indicator score)	$S = f\left(\frac{TEU}{GDP}\right)$	$S^* = f\left(\frac{TEU-NETVEU}{GDP-NE}\right)$
4	8.4 Improve resource efficiency in consumption and production	8.4.2 (1) Domestic material consumption per capita	$S = f\left(\frac{MC}{POP}\right)$ MC, domestic material consumption. POP, population.	$S^* = f\left(\frac{MC-NEVM}{POP}\right)$ NEVM, net exported virtual material embedded in international trade.
		8.4.2 (2) Domestic material consumption per GDP (low material intensity indicates high SDG indicator score)	$S = f\left(\frac{MC}{GDP}\right)$	$S^* = f\left(\frac{MC-NEVM}{GDP-NE}\right)$
5	9.4 Promote clean and sustainable industrialization	9.4.1 (1) CO_2 emissions per unit of value added (low carbon intensity indicates high SDG indicator score)	$S = f\left(\frac{CE}{GDP}\right)$ CE, domestic CO_2 emissions.	$S^* = f\left(\frac{CE-NEC}{GDP-NE}\right)$ NEC, net exported CO_2 emissions responsibility embedded in international trade.
		9.4.1 (2) CO_2 emissions from fuel combustion	$S = f(CE_{fc})$ CE_{fc}, CO_2 emissions from fuel combustion.	$S^* = f(CE_{fc} - NECE_{fc})$ $NECE_{fc}$, net exported CO_2 emissions responsibility from fuel combustion.
6	12.2 Achieve sustainable management and efficient use of natural resources (same indicators in the official indicator book: 8.4.2/12.2.2)	12.2.2 (1) Domestic material consumption per capita (low value indicates high SDG indicator score)	$S = f\left(\frac{MC}{POP}\right)$	$S^* = f\left(\frac{MC-NEVM}{POP}\right)$
		12.2.2 (2) Domestic material consumption per GDP (low material intensity indicates high SDG indicator score)	$S = f\left(\frac{MC}{GDP}\right)$	$S^* = f\left(\frac{MC-NEVM}{GDP-NE}\right)$
7	13.2 Take urgent measures to combat climate change and its impacts	13.2. CO_2 emissions intensity of areas under forest management ($GtCO_2$-equivalent per ha)[59] (low value indicates high SDG target score)	$S = f\left(\frac{CE}{FA}\right)$ FA, forest area.	$S^* = f\left(\frac{CE-NEC}{FA}\right)$
8	15.1 Ensure sustainable use of terrestrial ecosystems	15.1.1 Forest area as a proportion of total land area (high value indicates high SDG indicator score)	$S = f\left(\frac{FA_t}{TL}\right)$ FA_t, forest area in year *t*. TL, total land area.	$S^* = f\left(\frac{FA_t+NEVF_t}{TL}\right)$ $NEVF_t$, net exported virtual forestland embedded in international trade.
9	15.2 Promote sustainable forest management	15.2.1 Progress towards sustainable forest management (forest area net change rate as a measure)	$S = f\left(\frac{FA_t-FA_{base}}{FA_{base}}\right)$ FA_{base}, forest area in the baseline year.	$S^* = f\left(\frac{FA_t+NEVF_t-FA_{base}}{FA_{base}}\right)$

We normalize the SDG indicator scores ranging from 0 to 100; high scores represent good performance on achieving the SDG targets, while low scores stand for poor performance. For the sake of simplification, we use the functional symbol $f(x)$ to indicate the normalization algorithm. In the algorithm, we score all indicators so that high scores after normalization represent progress towards achieving the target. For example, indicators that represent negative meanings before normalization (for example, indicators 6.4.2, 7.3.1, 8.4.2, 9.4.1 and 13.2) are transformed to positive meanings to keep them consistent (the larger the score, the better the meaning for sustainability).

the categories and production of services and goods and limit the impacts of trade. Because adjacent countries usually produce similar goods, distant trade can diversify the services and goods a country imports and can make full use of comparative advantages, which is one of the fundamental arguments in favour of trade. Future research on sustainable development should differentiate the effects of trade with distant systems compared with local systems to uncover unexpected differences in socio-economic and environmental consequences. Our findings also suggest that international trade agreements should consider the environmental spillovers, such as the potential impacts of virtual resource consumption (for example, virtual water, energy and land use) and the accompanying displacement of environmental burdens (for example, CO_2 emissions) embedded in international trade[13]. Because developed countries tend to displace CO_2 emissions to developing countries[5,37], policies can set consumption-based targets that attribute the responsibility for CO_2 emissions to consumers instead of only to producers[37].

This research lays a foundation for further exploring the impacts of international trade on sustainable development across multiple dimensions, such as environmental conservation, economic development and social inclusion. Our results suggest the need to study the socio-environmental impacts of international trade and the impacts of embedded virtual resources on achieving the SDG targets. These impacts have substantial implications for rethinking global policy-making and reframing debates on environmental responsibilities among consumers, producers and traders across the world. In addition to traditional place-based governance approaches, it is important to take a flow-based approach that considers a place in light of its relationships with other places, by tracking and managing where key flows start, progress and end[38]. Flow-based governance can also directly target the flows themselves (for example, policies aimed at reducing high-resource-intensity flows of goods through certification schemes). We note that while most literature focuses on government policy, private-sector actors can have considerable impacts through the management of international supply chains[39]. Future studies therefore should also incorporate more SDG targets and indicators (covering environmental, socio-economic, finance, security and governance aspects)[40] and explore the impacts of international trade on trade-offs and synergies between achieving different SDGs. Such knowledge will be useful for maximizing the positive impacts and minimizing the negative impacts of international trade on sustainable development to better achieve global sustainability and improve human well-being. Further elucidation of the mechanisms by which trade generates cross-national inequities would also be helpful in formulating specific effective policies to achieve the SDGs.

Methods

Data. We obtained multiregional input–output (MRIO) tables from the World Input–Output Database (WIOD)[41]. The WIOD is perhaps the best-developed global database on trade flows among countries, with 35 sectors (for example, agriculture, mining and transport) for 40 countries that account for 97% of the world's GDP and for the rest of the world (see Supplementary Table 1 for the whole list of the countries and regions). The temporal coverage is from 1995 to 2009 (ref. [42]). This spatial, temporal and sectoral coverage allows us to track changes in the effects of international trade on achieving nine environment-related SDG targets over time, giving this study a broader scope than other relevant studies, which often focus on one sector or on a single aspect of sustainable development[4,43]. Environmental data (water consumption, energy consumption, raw material consumption, CO_2 emissions and land use) for each country from 1995 to 2009 were obtained from the WIOD (refer to ref. [44] for detailed data descriptions and definitions; see the data statistical description in Supplementary Fig. 5). Country-level data on GDP, human population, forest coverage and renewable internal freshwater resources from 1995 to 2009 were derived from the World Bank database[31].

Indicators for the SDG targets. The SDG indicators in this study (Table 1) were selected from the *United Nations' Global Indicator Framework for the Sustainable Development Goals* developed by the Inter-Agency and Expert Group on SDG Indicators (IAEG-SDGs)[45] and the *Indicators and Monitoring Framework for the Sustainable Development Goals* developed by the UN Sustainable Development Solutions Network (SDSN)[1]. We selected the SDG indicators on the basis of the following two criteria: (1) the indicators can be quantified according to the indicator description in the UN IAEG-SDGs indicator book or the SDSN SDGs book, and (2) the data for quantifying the SDG indicators are available from the WIOD. Taking SDG 6 as one example, we chose the target SDG 6.4 and its indicator 6.4.2 ("level of water stress: freshwater consumption as a proportion of available freshwater resources") as one of the quantitative indicators in our analysis, because data are available for freshwater consumption at the national level, and embedded water in international trade can be quantified by MRIO analysis using data from the WIOD. However, other indicators under SDG 6 (for example, SDG 6.5.1: "degree of integrated water resource management implementation" and SDG 6.6.1: "change in the extent of water-related ecosystems over time") were not clearly defined in terms of quantification, and their relationships to international trade are also difficult to quantify[1]. Given that different indicators under the same target can reflect different dimensions of this target, we thus took the mean value of these indicator scores as the target score if there are more than one indicator under this target. This approach is consistent with the SDSN SDG reports for 2016, 2017, 2018 and 2019 (https://www.sdgindex.org).

A hypothetical no-trade scenario for estimating the impacts of trade on achieving the SDG targets. Following previous research on trade scenarios[46,47], we used a hypothetical no-trade scenario to estimate the impacts of current international trade on achieving the SDG targets in the current world, but not to predict or depict a viable future. In such a hypothetical scenario, we added trade balance (exports minus imports) back into resource supplies. Countries' SDG target performances under a no-trade scenario were therefore calculated by adding the trade balance (that is, net exports) back to the exporters and then calculating the SDG indicator scores[46,47]. For example, the SDG 6.4.2 score under the existing trade conditions was evaluated using the water stress index (WSI), which is the ratio of a country's domestic water consumption to its domestic renewable freshwater resources (see equation (1)). Under the no-trade scenario, there would be no virtual water imports or exports between countries. Thus, a net exporting country would consume less domestic water (because the water is used only for domestic consumption and is not exported to other countries in this scenario), resulting in less water stress. The net exported water portion therefore represents the influence of international trade on the country's water stress[46]. The WSI under this hypothetical no-trade scenario (WSI*) can be calculated using equation (2).

$$\mathrm{WSI} = \mathrm{WU}/\mathrm{WR} \tag{1}$$

$$\mathrm{WSI}^{*} = (\mathrm{WU} - \mathrm{NEVW})/\mathrm{WR} \tag{2}$$

where water use (WU) is a country's total domestic water consumption under the trade scenario (water consumption in the real world)[44]. Internal water resources (WR) are a country's renewable freshwater resources. NEVW is the net exported virtual water. Under the no-trade scenario, a country's water consumption would be the difference between WU and NEVW, as the focal country would not export or import virtual water. We acknowledge that it is possible that a water-abundant country under the no-trade scenario might consume more water than we estimate (that is, WU – NEVW), and admittedly, this approach must be seen as an approximation given the complex economic dynamics that might unfold in the absence of trade. But we believe that this approach can provide a useful approximation. We used these methods to calculate the metrics for the other SDG target scores under a no-trade scenario to estimate the impact of international trade on sustainable development (Table 1).

MRIO analysis for quantifying virtual resource flows embedded in international trade. We applied MRIO analysis to quantify virtual water, CO_2, energy, raw materials and land embedded in international trade from 1995 to 2009. The virtual resource concept is an extension of the virtual water concept, which refers to the amount of natural resources required along the supply chain for the production of goods and services[5,13,29,46,48,49]. For instance, for environmental burdens such as CO_2, virtual resource consumption is the CO_2 emissions produced during the entire production and supply chain of goods and services.

MRIO analysis has been widely used to study economic interdependencies between countries by tracking monetary flows. Assuming that there are m countries and every country has n sectors, the monetary output of sector i in country R can be calculated using the following equation:

$$x_i^R = \sum\nolimits_{Q=1}^{m} \sum\nolimits_{j=1}^{n} x_{ij}^{RQ} + \sum\nolimits_{Q=1}^{m} y_i^{RQ} \tag{3}$$

where x_{ij}^{RQ} is the value of monetary flows from sector i of country R to sector j of country Q, and y_i^{RQ} represents country Q's final demand that is supported by sector i of country R.

The direct input coefficient a_{ij}^{RQ} is derived from equation (4):

$$a_{ij}^{RQ} = x_{ij}^{RQ}/x_j^{Q} \tag{4}$$

where a_{ij}^{RQ} is the value of monetary flows from sector i of country R that contributes to one unit of monetary output in sector j of country Q.

If we let $X = \left[x_i^R\right]$, $A = \left[a_{ij}^{RQ}\right]$ and $Y = \left[y_i^{RQ}\right]$, we can calculate the following matrix X using equation (5):

$$X = A \times X + Y \tag{5}$$

We then rearranged and formulated equation (5) as:

$$X = B \times Y;\ B = (I - A)^{-1} \tag{6}$$

where $(I - A)^{-1}$ is the Leontief inverse matrix, suggesting both direct and indirect flow of monetary value from other countries to meet one unit of final monetary demand.

To calculate the amount of virtual resources embedded in international trade, we first calculated the direct resource intensity coefficient. The direct resource intensity coefficient of sector i in country R is expressed as:

$$e_i^R = w_i^R/x_i^R \tag{7}$$

where w_i^R is the total resource/material intensity in sector i of country R; therefore e_i^R is the amount of resource/material consumed or emitted to increase one monetary unit of output in sector i in country R.

If we let $E = \left[e_i^R\right]$, then we can calculate the virtual resource (VR) transfer matrix using the following equation[5]:

$$\mathrm{VR} = E \times B \times Y \tag{8}$$

The amounts of virtual water, energy, material, CO_2 and forest embedded in yearly trade for each country/region from 1995 to 2009 are summarized in Supplementary Fig. 6. A more detailed description of global virtual resource flows can be found in our earlier publication[50].

SDG target scoring normalization. We calculated SDG target score metrics (Table 1) for all 41 countries/regions from 1995 to 2009. To achieve comparability of scores across different SDG targets, we normalized the indicator data on a scale of 0 to 100. To normalize the indicator data, we first established an upper bound (x_{max}, where x stands for each SDG indicator value) and a lower bound (x_{min}) for each SDG indicator[51]. SDG indicator values that represented higher performance than the upper bound received a score of 100, while values that represented performance below the lower bound received a score of 0. We set the data points at the top 2.5th percentile and at the bottom 2.5th percentile of all countries' SDG indicator performances for a given SDG indicator as the upper bound and lower bound, respectively. This upper and lower bound selection method can prevent skewed (for example, spurious variability) index rankings, which are often sensitive to extreme values (or outliers) in both tails of the data distribution. This bound selection method is consistent with the approach recommended by the Organisation for Economic Co-operation and Development for comparing and ranking indicator performances[52] and has been used by SDG research articles[51,53] and the SDSN SDG Index and Dashboards Report[40,54].

After obtaining the upper and lower bounds, we normalized the SDG indicator values across countries and over time on a scale of 0 to 100 by using the following formula[40,54]:

$$x' = (x - x_{\min})/(x_{\max} - x_{\min}) \quad (9)$$

where x' represents the normalized individual score for a given SDG indicator. Normalization allowed us to compare scores across different SDG indicators. The scores range from 0 to 100 and indicate a country's performance. A score of 0 indicates the worst performance, and a score of 100 indicates the best performance. A country with a score of 50 is halfway towards achieving the best performance. This method measures the SDG targets in linear intervals and ranks countries on the basis of their relative performance in achieving the SDG targets. To reflect the temporal change of a country's performance in the SDG targets, the values of SDG indicator metrics over time were pooled together so that there was only one lower and one upper bound value for normalization. Normalized indicator scores also reflected a country's absolute (instead of relative) improvement in sustainable development. For example, if a country lagged behind all other countries but improved over time, its SDG target score at the end of this period would be higher than its score at the beginning.

After normalizing the indicator metrics and calculating individual scores for each SDG target, we aggregated all nine normalized SDG target scores to yield a SDGct score as the arithmetic mean of the individual normalized SDG target scores[40,54]. The SDGct score represents the overall performance in achieving all evaluated SDG targets. Following the SDG Index and Dashboards Reports[40,55] and SDG research articles[51,54], all nine SDG targets were weighted equally in producing the aggregate measure, since there is no a priori reason to give one measure greater weight than another[40,54]. The equal weighting is also consistent with the spirit that all countries need to achieve the SDGs and targets through integrated strategies that address the full set of goals[40,54]. Changes in countries' SDGct scores over time indicated their progress in achieving the SDG targets at the national level. To track progress in achieving global SDG targets, we calculated the SDGct score at the global level by taking the mean of the SDGct scores across all countries without weighting for population or size of the economy, since the nation is the basic unit to implement efforts for achieving SDG targets, and all committed nations are required to achieve SDG targets. Additional analyses and discussions on weighting by GDP, by population and by GDP per capita can be found in Supplementary Fig. 7. The resulting trends from using these weighting methods are similar to what we reported here, especially when comparing our current equal weighting method and the GDP weighting analysis.

Country income groups. The countries were grouped into 28 developed countries and 13 developing countries/regions using the World Bank's classification based on income[31], which is consistent with the classification based on the Human Development Index[56,57] (Supplementary Table 1). We then calculated the average SDG target score for each country in each group, again without weighting for country population or GDP. We also classified international trade into adjacent trade and distant trade on the basis of the geographical relationships between countries. For example, trade between countries that share land or maritime borders was deemed as adjacent trade. In all other cases, trade between two countries or regions was deemed as distant trade (see Supplementary Table 2 for adjacent and distant trade partners)[16,17]. This allowed us to assess the impacts of adjacent versus distant trade on the SDG target scores in trading countries.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

All the source data described in the 'Data' section can be obtained from the World Input–Output Database (WIOD) and World Bank. The intermediate data that support the findings of this study are available from the corresponding author upon reasonable request. Source data are provided with this paper.

Code availability

All computer code used in conducting the analyses summarized in this paper is available from the corresponding author upon reasonable request.

Received: 23 July 2018; Accepted: 12 June 2020;
Published online: 13 July 2020

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Acknowledgements

We thank R. M. Scarrow and S. Nichols for their constructive comments that have greatly helped improve the paper. We are grateful for financial support from the National Science Foundation (grant nos DEB-1924111 and DEB-1340812), Michigan State University, Michigan AgBioResearch, the Environmental Science and Policy Program (ESPP) Doctoral Recruiting Fellowships and the China Scholarship Council.

Author contributions

Z.X., Yingjie Li and J.L. designed the research. Z.X. and Yingjie Li contributed the data. Yingjie Li and Z.X. performed the data analysis and interpreted the results with support from S.N.C., J.L., T.D., C.L., L.W., J.Z., L.Z., Yunkai Li and M.G.C. Yingjie Li, Z.X. and J.L. wrote the manuscript with contributions from S.N.C. and T.D. All authors reviewed and commented on the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41893-020-0572-z.

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Study description	While the United Nations has adopted 17 Sustainable Development Goals (SDGs) with 169 targets and international trade has substantial influences on global sustainability and human well-being, little is known about the impacts of international trade on progress towards achieving SDG targets. Here we show that international trade positively affected global progress towards achieving nine environment-related SDG targets. International trade improved the SDG target scores of most (65%) of the evaluated developed countries but reduced the SDG target scores of over 60% of the evaluated developing countries. The SDG target scores of developed countries were higher than those of developing countries when trade was accounted for, but those scores would be lower than developing countries were trade not a factor. Further, trade between distant countries contributed more to achieving these global SDG targets than trade between adjacent countries. Compared to adjacent trade, distant trade was more beneficial for achieving SDG targets in developed countries, but more negatively affected SDG target scores in developing countries. Our research suggests that enhancing the accounting for and management of virtual resources embedded in trade is essential for achieving and balancing sustainable development for all.
Research sample	We calculated SDG target score for 41 countries/regions from 1995 to 2009. The countries/regions were grouped into 28 developed countries and 13 developing countries/regions using the World Bank's classification.
Sampling strategy	We calculated SDG target score for 41 countries/regions from 1995 to 2009. The countries/regions were grouped into 28 developed countries and 13 developing countries/regions using the World Bank's classification.
Data collection	All the data used for this study were downloaded from the World Input-Output Database (WIOD) and World Bank Database.
Timing and spatial scale	We calculated SDG target score for 41 countries/regions from 1995 to 2009.
Data exclusions	All data are included.
Reproducibility	We have provided data source information to ensure reproducibility.
Randomization	The countries/regions were grouped into 28 developed countries and 13 developing countries/regions using the World Bank's classification. We also classified international trade into "adjacent trade" and "distant trade" based on the geographical relationships between countries (This classification was based on Ref 16 and 17).
Blinding	No blinding.

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