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Evidence of decoupling consumption-based CO_2 emissions from economic growth

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ABSTRACT

Decoupling economic growth from resource use and emissions is a precondition to stay within planetary boundaries. A number of countries have achieved a reduction in their production-based emissions in the past decade. However, the decline in PBE has often been achieved via outsourcing of emissions to other countries, which may even lead to higher emissions globally. Therefore, a consumption-based perspective that accounts for a country's emissions along global supply chains should also be employed when investigating progress in decoupling. Here we investigate the progress countries made in reducing their production-based and consumption-based emissions despite growth in gross domestic product (GDP). We found that 32 out of 116 countries (mainly developed ones) achieved absolute decoupling between GDP and production-based emissions in recent years (2015–2018), and 23 countries achieved absolute decoupling between GDP and consumption-based emissions. 14 countries have decoupled GDP growth from both production- and consumption-based emissions. Even countries that have achieved absolute decoupling are still adding emissions to the atmosphere thus showing the limits of 'green growth' and the growth paradigm. We also observed that decoupling can be temporary, and decoupled countries may switch back to increasing emissions, which means that continuous efforts are needed to maintain decoupling. An analysis of driving factors shows that whether a country can achieve decoupling mainly depends on reducing emission intensity along domestic and import supply chains. This highlights the importance of decarbonizing supply chains and international collaboration in controlling emissions.

Introduction

Given that economic growth is a major political goal (at least for developing countries), decoupling growth from resource use and emissions is a precondition to stay within planetary boundaries [1],[2]. Green growth theories claim that continued economic expansion is compatible with environmental goals, as technological progress and continual substitution allow us to stay within global planetary limits [3]. This discussion goes back at least to the Limits of Growth [4], and has been part of dominant policy discourses such as the Brundtland report [5,6] and the Sustainable Development Goals stating that "sustained and inclusive economic growth can drive progress, create decent jobs for all and improve living standards" [7]. Most recently, the European Parliament decided to push for targets to reduce resource use by 2030 and bring EU consumption within planetary boundaries by 2050 [8]. After 40 years of promoting economic growth, the OECD now also recognizes that instead of focussing on GDP, the emphasis of economic policies should rather be on increasing human wellbeing, environmental sustainability, resilience, and decreasing inequality [9]. This follows calls from the scientific community to explore the potential of post-growth or degrowth policies in developed countries to achieve sustainable levels of production and consumption [10,11].

Green growth or decoupling describes the relationship between economic growth and resource consumption and environmental impacts, respectively. Decoupling happens when the increase of an environmental pressure or impact in a country/region is slower than the growth of GDP for a given period. There has been a longstanding discussion on whether environmental impacts such as carbon emissions and the use of natural resources can be decoupled from economic growth. Although it is controversial whether absolute decoupling can be achieved at a global scale [3,12–15], a number of studies found some evidence for decoupling at the national level. For example, Wang and Su [16] examined the extent of decoupling in 192 countries from 2000 to 2014 and found that most of the developed countries have achieved relative decoupling

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(i.e., emissions increase being slower than GDP growth) and are moving towards absolute decoupling while most developing countries have not decoupled. Similar comparisons between developed and developing countries have been provided by Wu, Zhu [17]. Numerous studies have investigated the extent of decoupling for individual countries such as Greece [18], or developing countries such as Pakistan [19] and Brazil [20], or at a finer scale of economic sectors [21,22] and cities [23–25].

Most of these studies calculated a decoupling index based on production-based or territorial emissions [24,25]. Production-based emissions (PBE) and territorial emissions resulting from the production and consumption of goods and services within a region as well as for export production are often used by authorities to report carbon emissions [26,27]. Using such an index would not account for the fact that over the last decades, high-income nations have shifted a large share of their more carbon-intensive production abroad, and their consumers have increased their demand for imported products [28,29], both have led to an increase in emissions abroad. If we use only territorial or production-based measures, and not accounting for such production and consumption shifts and outsourcing of pollution, these countries would be more likely to show decoupling or green growth, at the expense of exporting countries [28,30–37]].

In contrast, consumption-based emissions (CBE) refer to emissions along the entire supply chains induced by consumption irrespective of the place of production [38,39]. This reflects a shared understanding that a wider system boundary going beyond territorial emissions is important to avoid outsourcing of pollution and to achieve global decarbonization. CBE accounting allows to identify new policy levers through providing information on a country's trade balance of embodied emissions, household's carbon implications of their lifestyle choices, companies' upstream emissions as input for supply chain management, and cities' often considerable footprints outside their administrative boundaries [28,40].

A number of studies investigated the topic of decoupling of consumption-based emissions in several countries/regions. For example, Mir and Storm [41] compared the extent of decoupling of 40 countries from both production- and consumption-based approaches and found that although these countries' economic growth was decoupled from production-based emissions, their consumption-based emissions were monotonically increasing with per-capita GDP. Some studies further used structural decomposition analysis (SDA) to analyze the drivers of decoupling between GDP, CBE and trade embodied emissions [42,43]. For example, Kulionis and Wood [44] calculated the degree of decoupling of consumption-based energy (energy footprint) and GDP in high-income countries and explored the drivers with SDA. However, none of these studies did a global anlaysis of decoupling of CBE and GDP.

Therefore, this paper discusses the extent of decoupling of economic growth and consumption-based emissions in 116 countries from 1990 to 2018, using the datasets from the Global Carbon Budget 2020 [45]. We apply structural decomposition analysis (SDA) to explore the driving forces of changes in consumption-based emissions in countries with different degrees of decoupling using the Global Trade Analysis Project (GTAP) multiregional input-output database [46]. Our study provides new insights to the discourse on green economic growth and decoupling and sheds light on the state of global low-carbon development and climate change mitigation.

Methods and materials

Consumption-based emissions accounting

There are several scopes to account CO_2 emissions of a country. Production-based emissions (PBE) and territorial emissions resulting directly from the production and consumption of goods and services within a region are often used by authorities to report carbon emissions [26,27,47]. However, consumption in a country is increasingly met by global supply chains oftentimes involving large geographical distances and causing emissions in producing countries [48–50]. Therefore, accounting emissions along the entire supply chain to fulfill the final demand of a country, so-called consumption-based emissions (CBE), is necessary to understand why emissions occur and to what extent consumption choices and associated supply chains contribute to total emissions, and ultimately how to manage consumption to achieve climate mitigation targets and environmental justice [51].

The most widely used method for calculating consumption-based emissions (CBE, or 'carbon footprints') of nations is global multi-region input-output (GMRIO) analysis [52]. The basic linear equation in the MRIO framework can be represented as

$$\begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} & \cdots & B_{1n} \\ B_{21} & B_{22} & \cdots & B_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ B_{n1} & B_{n2} & \cdots & B_{nn} \end{bmatrix} \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix} \tag{1}$$

where X is the global total output vector and X_r is the total output vector of region r, B represents the global Leontief inverse matrix, which is the total input coefficients matrix capturing both direct and indirect input requirements to meet one unit of final demand for each sector in each country, $B = (I - A)^{-1}$, where I is the identity matrix, A is the direct consumption coefficient matrix which represents the amount of direct inputs required for producing \$1 of a good or service, Y is the final demand matrix, and Y_{sr} refers to the direct imports of products from region s to meet the final demand of region r .

According to the standard CBE accounting model based on the MRIO framework [28,53], region r's CBE can be formulated as follows:

$$CBE_r = fBY_{*r} \tag{2}$$

where f refers to the global emission coefficient vector, which represents CO_2 emissions per unit of economic output for all sectors in all countries; Y_{*r} is the final demand vector of region r.

Generally, the uncertainty of CBE results depend on the choice of the dataset/model used for calculation, which differs in terms of a) national economic and trade data, b) emissions data, c) sector or product-level aggregation, d) countries resolution, e) conceptual scope (e.g., residential vs. territorial accounting principle), and f) model construction techniques which include algorithms for balancing the tables and ways of dealing with missing or conflicting data [54–58]. When excluding systematic error sources, previous studies have shown that the stochastic variation of national CBE accounts is not significantly different to PBE accounts and in the region of 5–15% [58–60]. For example, Wood, Moran [57] present the first comprehensive and systematic model intercomparison and find a variation of 5–10% for both PBE and CBE accounts of major economies and regions using different MRIO database.

Decoupling analysis

We employ the decoupling analysis to examine the relative speed of economic growth and CO_2 emissions. The decoupling index can be calculated based on the changes of their GDP and emissions [17,25,61]. See the equation below.

$$DI = \frac{\Delta GDP\% - \Delta Em\%}{\Delta GDP\%} = 1 - \left(\frac{Em_1 - Em_0}{Em_0} \Big/ \frac{GDP_1 - GDP_0}{GDP_0} \right) \tag{3}$$

DI refers to the decoupling index; GDP_1 refers to GDP of the reporting year while GDP_0 refers to the base year; Em_1 refers to CO_2 emissions (consmption- or production-based) of the reporting year while Em_0 refers to emissions of the base year. Absolute decoupling refers to a decline of emissions in absolute terms or as being stable while GDP grows (i.e., a decoupling index greater than 1); relative decoupling refers to the growth of emissions being lower than the growth of GDP (a decoupling index between 0 and 1); and no decoupling, which refers to a situation where consumption-based emissions grow to the same extent or faster than GDP (a decoupling index of less than 0) [17]. Countries with declining GDP are clustered as another group pf economic recession.

Structural decomposition analysis

By employing structural decomposition analysis (SDA) [29,62,63], we can distinguish the contribution of different factors to the change of CBE. This approach has also been widely used to investigate drivers of other air pollutants such as SO_2 emissions [64,65], and water [66] and energy footprints [44]. In this paper, the SDA method is used for distinguishing domestic and foreign countributing factors for the changes in a country's CBE.

The change in the CBE of region *r* from the base year to the finalyear can be expressed as

$$\Delta CBE_r = CBE_r^1 - CBE_r^0 = f^1 B^1 Y_{*r}^1 - f^0 B^0 Y_{*r}^0 \tag{4}$$

where superscript 0 reflects the base year and superscript 1 reflects the final year.

The Leontief inverse (B) is a combined component of the trade structure of inputs and production technology. To separate the changes in CBE induced by trade and technology changes, we disentangle the direct input coefficient (A) from the inputs trade matrix (T) and domestic production coefficients matrix (H), $A = T \otimes H$ [67],69,70]. In this way, the Leontief inverse with a distinction of trade structure of inputs and production structure is $B = (I - T \otimes H)^{-1}$. Here, $\otimes$ is the Hadamard product, which is the cell-by-cell multiplication.

Meanwhile, considering the rapid development of global fragmentation in recent decades, changes in foreign countries may have crucial impacts on a region's CBE. We disentangle domestic and foreign factors to trace the impacts stemming from domestic and abroad [68]. Using superscript "*d*" indicates domestic factors, and superscript "*f*" indicates foreign factors, the final demand of region *r* ($Y_{*r} = \begin{bmatrix} Y_{1r} & Y_{2r} & \cdots & Y_{nr} \end{bmatrix}'$) can be distinguished as consumption of domestic products and imports.

$$Y_{*r} = Y_{*r}^d + Y_{*r}^f = \begin{bmatrix} 0 & Y_{rr} & \cdots & 0 \end{bmatrix}' + \begin{bmatrix} Y_{1r} & 0 & \cdots & Y_{nr} \end{bmatrix}' \tag{5}$$

We also do this for emission intensity (f) and trade structure of inputs (T), and production technology (H).

$$f = f^d + f^f = \begin{bmatrix} 0 & f_r & \cdots & 0 \end{bmatrix} + \begin{bmatrix} f_1 & 0 & \cdots & f_n \end{bmatrix} \tag{6}$$

$$T = T^d + T^f = \begin{bmatrix} 0 & 0 & \cdots & 0 \\ 0 & T_{rr} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 \end{bmatrix} + \begin{bmatrix} T_{11} & T_{12} & \cdots & T_{1n} \\ T_{r1} & 0 & \cdots & T_{rn} \\ \vdots & \vdots & \ddots & \vdots \\ T_{n1} & T_{n2} & \cdots & T_{nn} \end{bmatrix} \tag{7}$$

$$H = H^d + H^f = \begin{bmatrix} 0 & 0 & \cdots & 0 \\ 0 & H_{rr} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 \end{bmatrix} + \begin{bmatrix} H_{11} & H_{12} & \cdots & H_{1n} \\ H_{r1} & 0 & \cdots & H_{rn} \\ \vdots & \vdots & \ddots & \vdots \\ H_{n1} & H_{n2} & \cdots & H_{nn} \end{bmatrix} \tag{8}$$

Further, the consumption of domestic products (Y_{*r}^d) and imports (Y_{*r}^f) is decomposed to consumption patterns and consumption volume. Thus, $Y_{*r} = Y_{*r}^d + Y_{*r}^f = Ystr_{*r}^d \; Ylev_{*r}^d + Ystr_{*r}^f \; Ylev_{*r}^f$.

With the average of two polar decompositions [71], change of CBE is decomposedinto ten driving factors, including domestic emission intensity (Δf^d), foreign emission intensity (Δf^f), domestic trade structure of inputs (ΔT^d), foreign trade structure of inputs (ΔT^d), domestic production structure (ΔH^d), foreign production structure (ΔH^f), consumption patterns of domestic products ($\Delta Ystr^d$), consumption patterns of imports ($\Delta Ystr^f$), consumption volume of domestic products ($\Delta Ylev^d$), and consumption volume of imports ($\Delta Ylev^f$).

$$\Delta CBE_r = \Delta f^d \left(B^1 Y_{*r}^1 + B^0 Y_{*r}^0 \right) / 2 \tag{9a}$$

$$+ \Delta f^f \left(B^1 Y_{*r}^1 + B^0 Y_{*r}^0 \right) / 2 \tag{9b}$$

$$+ \left[f^1 B^1 \Delta T^d \otimes \left(H^{0d} + H^{1d} \right) B^0 Y_{*r}^0 + f^0 B^1 \Delta T^d \otimes \left(H^{0d} + H^{1d} \right) B^0 Y_{*r}^1 \right] / 4 \tag{9c}$$

$$+ \left[f^1 B^1 \Delta T^f \otimes \left(H^{0f} + H^{1f} \right) B^0 Y_{*r}^0 + f^0 B^1 \Delta T^f \otimes \left(H^{0f} + H^{1f} \right) B^0 Y_{*r}^1 \right] / 4 \tag{9d}$$

$$+ \left[f^1 B^1 \left(T^{0d} + T^{1d} \right) \otimes \Delta H^d B^0 Y_{*r}^0 + f^0 B^1 \left(T^{0d} + T^{1d} \right) \otimes \Delta H^d B^0 Y_{*r}^1 \right] / 4 \tag{9e}$$

$$+ \left[f^1 B^1 \left(T^{0f} + T^{1f} \right) \otimes \Delta H^f B^0 Y_{*r}^0 + f^0 B^1 \left(T^{0f} + T^{1f} \right) \otimes \Delta H^f B^0 Y_{*r}^1 \right] / 4 \tag{9f}$$

$$+ \left[f^1 B^1 \Delta Ystr^d Ylev_{*r}^{0d} + f^0 B^0 \Delta Ystr^d Ylev_{*r}^{1d} \right] / 2 \tag{9g}$$

$$+ \left[f^1 B^1 \Delta Ystr^f Ylev_{*r}^{0f} + f^0 B^0 \Delta Ystr^f Ylev_{*r}^{1f} \right] / 2 \tag{9h}$$

$$+ \left(f^1 B^1 Ystr_{*r}^{1d} + f^0 B^0 Ystr_{*r}^{0d} \right) \Delta Ylev^d / 2 \tag{9i}$$

$$+ \left(f^1 B^1 Ystr_{*r}^{1f} + f^0 B^0 Ystr_{*r}^{0f} \right) \Delta Ylev^f / 2 \tag{9j}$$

It should be noted that there are more than one possible ways of decomposition as more than one factors may drive the changes in CBE. If there are n elements in matrix multiplication, there will be n! possible ways of decomposition. Aside from the average of two polar decompositions, some studies argue that the average of all possible first-order decompositions would be a better choice [72,73]. To ensure robustness, we also calculate the SDA results based on the average of all possible first-order decompositions. Compared with the results based on the average of two polar decompositions (**Fig. 4**), we can see that in our case, the average of all possible first-order decompositions yields almost the same results **(Figure S5)**.

Data sources

We employ the PBE and CBE datasets from the Global Carbon Budget 2020 for the decoupling analysis [45]. The CBE in the Global Carbon Budget 2020 are based on economic and trade data from the Global Trade and Analysis Project (GTAP) for making detailed estimates for 1997, 2001, 2004, 2007, and 2011. Detailed results are then extended into an annual time series from 1990 to 2018 based on GDP data and trade data [45]. Compared with other databases for consumption-based emission accounting, such as WIOD and OECD ICIO, the CBE data in the Global Carbon Budget 2020 has the widest coverage of countries (116 countries) and the longest time series (1990–2018). Another alternative database is Eora. However, some studies have shown that the Eora database has large uncertainties in production structure and trade data estimated by the automated reconciliation process [56,74]. In addition, GDP (constant 2010 US$) and population data in our analysis come from the World Bank. We employ the latest GTAP MRIO (Version 10) for the structural decomposition analysis for its high accuracy in trade data, which is vital to examine the impacts of different internal and external driving factors on CBE. GTAP MRIOs cover 141 (Version 10) regions and 65 sectors for 2004, 2007, 2011, and 2014 [46]. To make the MRIO tables for different years comparable without price bias, we deflate the original current-price data to constant-price data. The price data is collected from National Account Main Aggregates Database

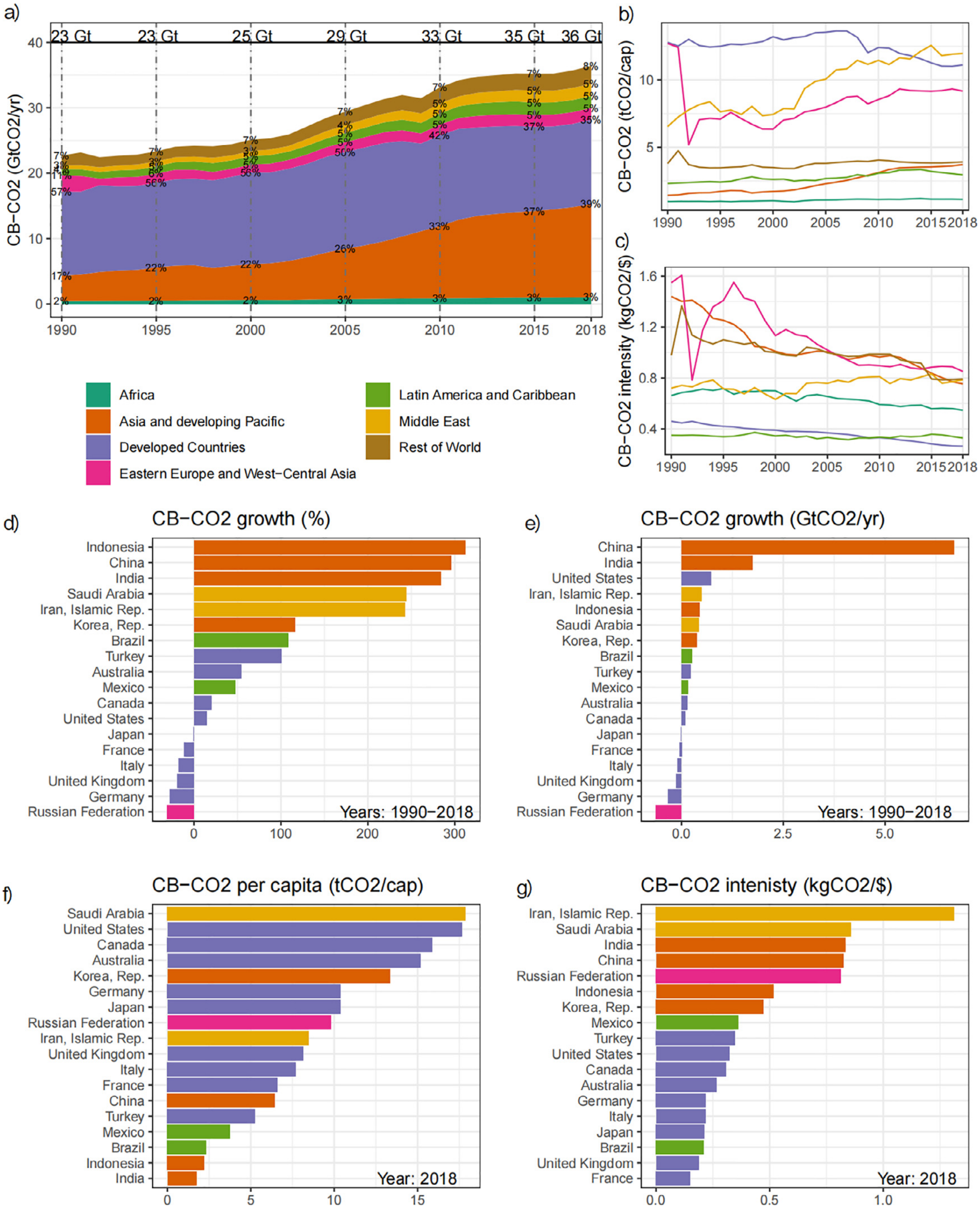

Fig. 1. Consumption-based (CB) CO_2 emissions trends for the period 1990–2018. The top three panels (a-c) show the total and per capita CBE and CBE intensity for six regions. The bottom four panels (d-g) show additional information for the top-emitting countries with the highest CBE in 2018. We adopt the United Nations country classification (M49 Standard) [79]. (Data source: Global Carbon Budget 2020 [45]).

and reallocated to the GTAP sectors, following the concordance table in Meng, Mi [63] (See **Table S1**). It should be noted that because GTAP MRIOs (Version 10) and the previous version have different numbers of countries and sectors, the aggregation of regions and sectors will bring aggregation errors while reducing the scope of our analysis [75–78]. Therefore, in the analysis of driving factors, to ensure the reliability of the results, we only analyze 2004, 2007, 2011, and 2014 included in the latest GTAP MRIOs with consistent sectoral and country resolutions (Version 10).

Results

Consumption-based emissions of countries and emissions embodied in trade

We present the CBE from six regions and top-emitting countries in Fig. 1. The results show that CBE of developed countries and in Asia and Developing Pacific are higher than in other regions. In developed countries, CBE peaked at 15 $GtCO_2$ in 2007 with a subsequent 16% decline until 2016 and a slight rebound of 1.6% until 2018. Asia and Devel-

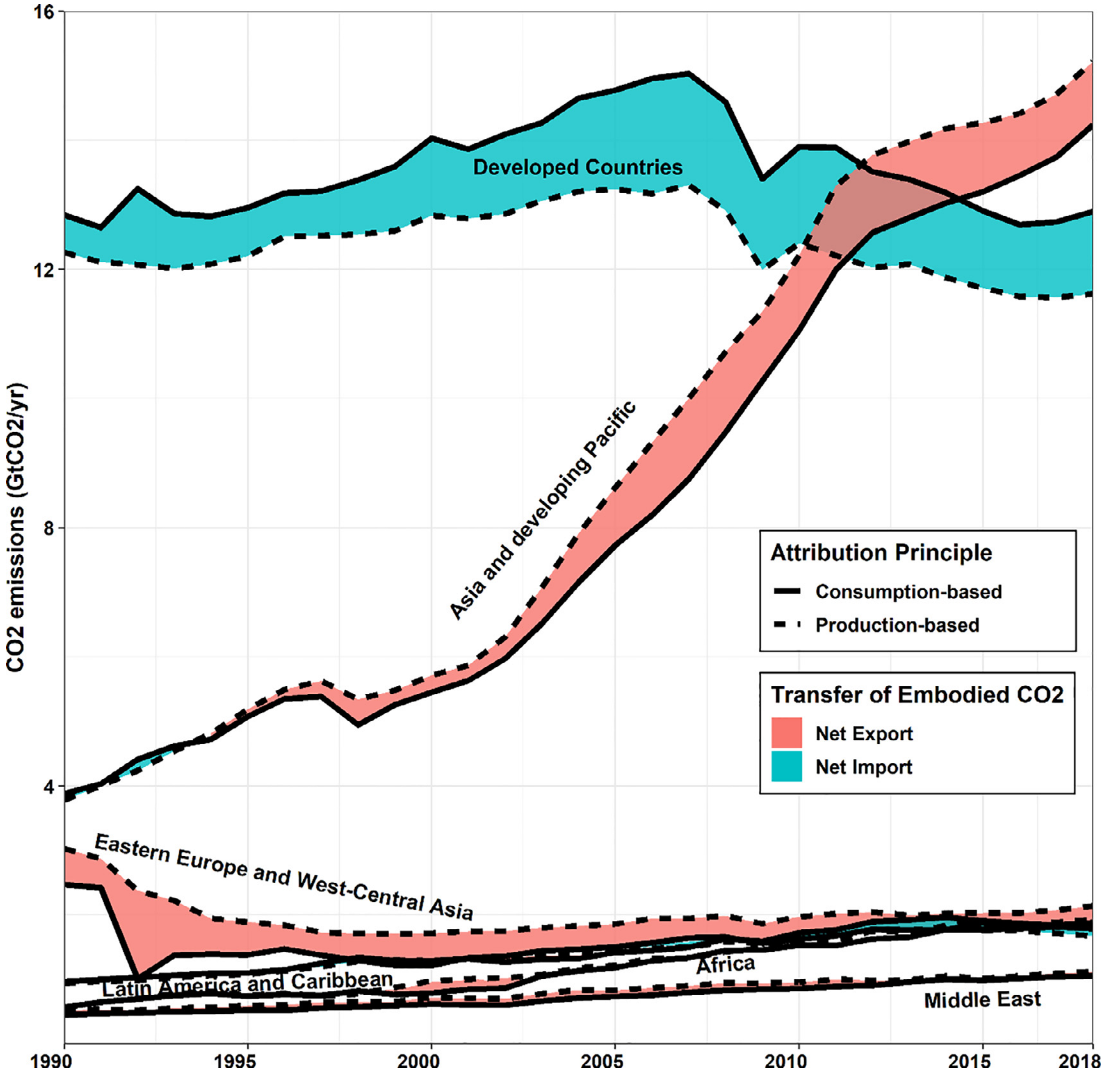

Fig. 2. CO_2 emissions by regions attributed on the basis of consumption and production-based emissions. (Data source: Global Carbon Budget 2020 [45]).

oping Pacific has been a major contributor to CBE growth since 2000 and exceeded the developing countries as the global largest emission source in 2015. The average growth rate of Asia and Developing Pacific was 5.5% per year (from 2000 to 2018), while other regions grew at −0.5% - +4.9%/year on average. In 2018, 35% of the global CBE were from developed countries and 39% from Asia and Developing Pacific, 5% from Latin America and the Caribbean, and 5% from Eastern Europe and West-Central Asia, 5% from Middle East, and 3% from Africa, respectively.

As global trade patterns have changed over recent decades, so have emissions embodied in trade (EET) [80]. EET includes two parts: emissions embodied in imports (EEI) and emissions embodied in exports (EEE). The net transfer of EET refers to emissions associated with the production of traded goods and services and is equal to a country's difference between PBE and CBE (i.e., $EEE - EEI = PBE - CBE$) [81]. Global EET have been rising faster since the 1980s due to an increase in trade volume [58,68]. CO_2 emissions from the production of internationally traded products peaked in 2006 at about 27% of global CO_2 emissions. Since then, international CO_2 emissions transfers declined but are likely to remain an important part of the climate policy agenda [82]. Calculations based on the GTAP MRIO show that about 24% of global economic output was traded, and 25% of global CO_2 emissions were embodied in international trade of goods and services in 2014.

For a given country or region with CBE higher than PBE, the country is a net importer with a higher EEI than EEE and vice versa. The shaded areas in Fig. 2 show the net CO_2 trade balances (differences) between each of the six country groups. Blue shading (mainly in developed countries) indicates that the country group is a net importer of embodied CO_2 emissions, leading to higher consumption-based emissions than production-based emissions. Red shading indicates the reverse, which is mainly the case in developing countries.

Decoupled economic growth from emissions

Fig. 3 shows the trends of CBE and GDP of country groups. During the most recent three-year period from 2015 to 2018, 23 countries (or 20% of 116 countries) have achieved absolute decoupling of CBE and GDP, while 32 countries (or 28%) achieved absolute decoupling of PBE and GDP. Only 14 countries have decoupled GDP growth from both PBE and CBE. Another 67 countries (or 58%) have relatively decoupled, and 19 (or 16%) coupled economic growth with CBE. 6 countries were in an economic recession (i.e., having a decline in their GDP) during the study period. It is important to note that a country's degree of decoupling changes over time. For example, 32 countries achieved absolute decoupling from 2010 to 2015, and only 10 of them remained decoupled over the next three years.

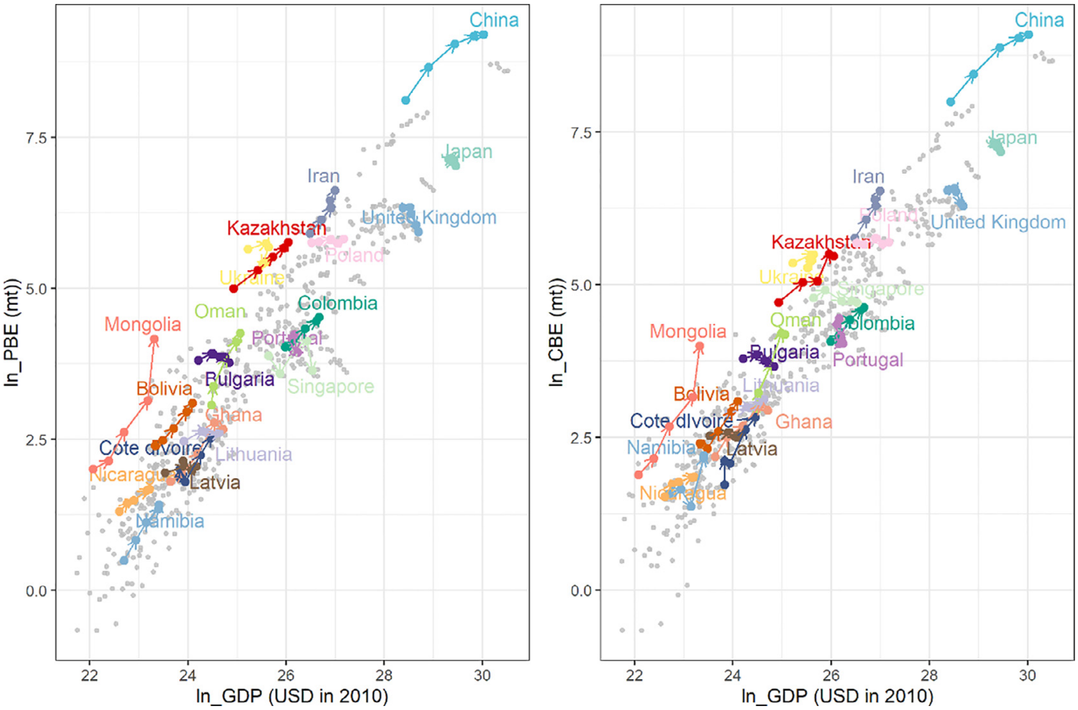

Fig. 3. Trends of emissions and GDP between 1990 and 2018. The Y-axis represents the natural logarithm of PBE and CBE and the X-axis shows the natural logarithm of GDP. The gray dots show the emissions vs. GDP of each country every five years from 1990 to 2015 and 2018. The countries in color dots are selected based on their degree of decoupling of CBE and GDP.

Table 1 shows that countries with absolute decoupling tend to achieve decoupling of CBE and PBE at relatively high levels of GDP and high per capita emissions. Most of the EU and North American countries are in this group. This reflects similar findings by Wood, Neuhoff [83], who found that EU countries have reduced their overall consumption-based GHG emissions by 8% between 1995 and 2015, mainly due to the use of more efficient technology, both domestically and in imports. In other words, decoupling was not only achieved by outsourcing pollution but also improvements in production efficiency and energy mix, leading to a decline of PBE and CBE [84].

Apart from those developed countries, we observed that some lower-income countries also achieved absolute decoupling of emissions and GDP. For example, Zimbabwe and Israel show absolute decoupling from both PBE and CBE over 2015–2018; Cameroon showed absolute decoupling of PBE and weak decoupling of CBE and GDP. However, such decoupling in lower-income countries might be exceptions and affected by exogenous factors, such as political instability, recessions, and data quality [57], and may frequently change over time. For example, Zimbabwe has switched back and forth between “absolute decoupling” and “no decoupling” for the past 25 years (1990 to 2015). Thus, the experience of decoupling in those less-developed regions cannot serve as role models for the rest of the world. Although the same can be said about developed countries and they decoupling given that this was only achieved at very high levels of per capita emissions.

A number of countries, such as China, and India, experienced relative decoupling of GDP and CBE from 2015 to 2018. However, as our CBE data only goes until 2018, some countries’ emissions may have again increased after a short period of decoupling [85,86].

Another 19 countries, such as South Africa and Nepal, have experienced no decoupling between GDP and emissions from 2015 to 2018, meaning their GDP growth is closely tied with domestic consumption and production of emission-intensive goods. As a result, further increase in GDP in these countries will likely lead to higher emissions if following the historical trend.

Driving forces for decoupling

We further investigate potential driving factors of CBE for countries with different decoupling types via structural decomposition analysis (Fig. 4). In general, whether decoupling can be achieved mainly boils down to a race between growth in consumption volume and decline in emission intensity.

For countries that have successfully achieved decoupling (absolute or relative), decreasing emission intensity of domestic production was the main driver of the decline in CBE (see red line in Fig. 4), contributing −21% and −17% of the change in total emissions in countries with absolute decoupling and relative decoupling, respectively. Foreign emission intensity is the second largest driver for reducing emissions, contributing −5.8% and −4.8% to the changes in CBE in those two groups. In comparison, countries without any decoupling had experienced an increase in emission intensity of domestic production, which contributed 5.6% to the changes in their CBE, although the emission intensity of imports has noticeably improved (contributing −7.9% of the total change in CBE).

In terms of emission drivers, excluding countries with economic recession, increasing consumption volume for domestic products was the biggest factor increasing CBE, especially in countries with relative decoupling and no decoupling (+80.2% and 58.0%, respectively). For decoupled countries, the impact of scale on CBE was +7.8%. The second factor increasing emissions in absolute decoupling countries was changes in consumption pattern for domestic products (+3.6%), whereas in countries showing only relatively decoupling or no decoupling, the increase in consumption volume for imports led to an increase of 4.8% and 11.1%, respectively.

In 2004–2014, the production technology effect (i.e., the input mix of intermediate goods) had a small impact on CBE in total (see green line in Fig. 4). However, specific to the three-time period, it showed significant fluctuations together with emission intensity in 2007–2011, especially for relatively decoupled countries. The change in domestic input

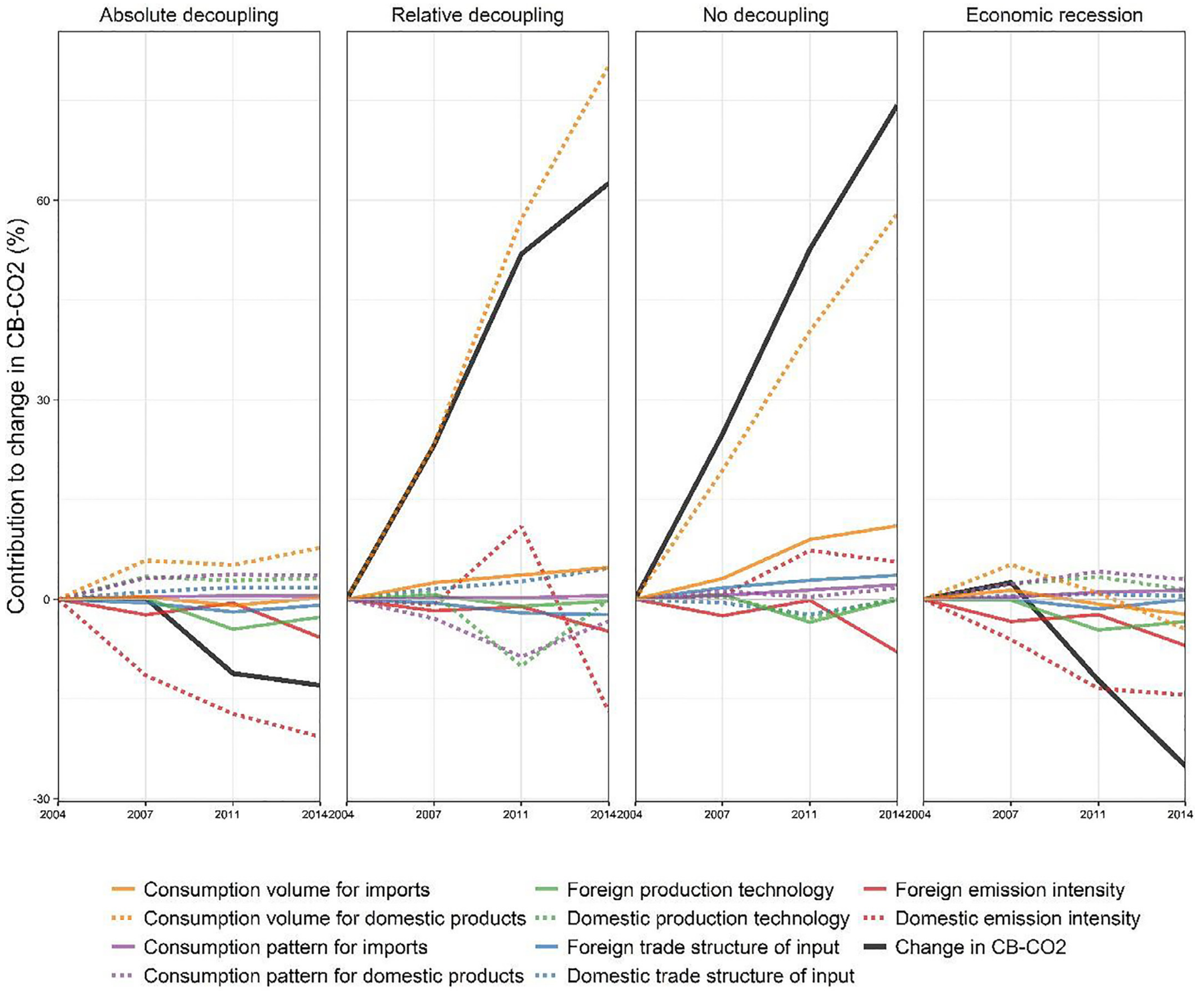

Fig. 4. Driving factors of consumption-based CO_2 emissions for different decoupling groups. Calculation based on GTAP MRIOs for 2004, 2007, 2011, and 2014. Dotted lines represent domestic drivers, and solid lines refer to factors abroad. See the detailed country-level results in Figure S1-S4.

mix had significantly reduced these countries' CBE (−10.0%). Changes in foreign production technology have led to a 4.5% decrease of CBE for absolutely decoupled countries and a 3.4% decrease for no decoupling countries driven by imports from relatively decoupled countries. However, this was a temporary effect in global supply chains induced by the global financial crisis.

Other factors, including trade structure of inputs (i.e., the pattern of international sourcing) and consumption pattern, had a limited impact on CBE. If a country purchases intermediate products from countries with relatively low-carbon intensity, the trade structure of inputs effect contributes to lowering CBE. However, our results show that the green transformation of the global supply chain has not led to significant improvements during the period 2004–2014 (−0.06% – +4.7% at home, and −2.28% – +3.61% abroad). Changes in consumption patterns also had a small impact on CBE (−3.33% – +3.6% at home, and +0.5% – +2.2% abroad).

Discussion

Although a number of countries have achieved absolutely decoupled economic growth from consumption-based emissions or production-based emissions, this did not stop the concentration of CO_2 in the atmosphere from continually rising to about 420 ppm in 2021 as measured at the Mauna Loa Observatory. Absolute decoupling is insufficient to avoid consuming the remaining CO_2 emission budget under the global warming limit of 1.5 °C or even 2 °C and avoid potential climate breakdown [3]. Overwhelming efforts are needed to reduce global emissions in line with Paris Agreement targets, and the evidence seems to be mounting that even widespread and rapid absolute decoupling alone might not suffice to achieve these goals without some form of economic degrowth [11,87,88].

Countries showing relative or no decoupling are mostly developing countries. Given the necessity for economic growth in developing countries, a much faster decline in domestic emission intensity is needed there.

The increase in demand for domestic products is the biggest contributor to boosting consumption-based emissions, while the reduction in domestic emission intensity can effectively lower consumption-based emissions. Whether a country achieved decoupling between 2004 and 2014 mainly depended on the relative magnitude of these two factors. For example, the increasing penetration of renewable energy in Europe and a structural shift from coal to gas power in the United States are

Table 1
Country groups with different degrees of decoupling between CBE and GDP for 2015–2018.

		Absolute decoupling	Relative decoupling	No decoupling	Economic recession
Number of countries		23	67	19	6
CBE (gigatons)	Total	5.40	25.33	1.93	0.85
	Global share	16.0%	75.3%	5.7%	2.5%
PBE (gigatons)	Total	4.84	25.73	2.16	0.84
	Global share	14.4%	76.3%	6.4%	2.5%
Population (million)	Total	625	5195	768	270
	Global share	9.1%	75.4%	11.5%	3.9%
GDP (billion)	Total	19,891	54,240	2300	2997
	Global share	25.0%	68.3%	2.9%	3.8%
Per capita GDP (thousand USD in 2010 prices)	Average	31.45	16.29	6.57	17.78
	Median	23.55	8.03	2.56	13.12
	Max	110.70	79.23	63.93	33.11
	Min	1.31	0.49	0.52	5.80
Per capita CBE (ton)	Average	10.27	5.30	4.47	12.55
	Median	8.87	4.13	1.67	11.33
	Max	37.95	17.65	25.35	23.21
	Min	0.64	0.09	0.18	2.33
CBE intensity (ton per thousand USD in 2010 prices)	Average	0.45	0.50	0.93	0.66
	Median	0.36	0.42	0.62	0.69
	Max	1.16	2.41	4.10	1.22
	Min	0.11	0.10	0.28	0.21
Per capita PBE (ton)	Average	8.20	4.36	5.32	14.15
	Median	6.79	3.02	1.19	13.22
	Max	19.58	20.13	39.27	27.24
	Min	0.49	0.09	0.08	2.23
PBE intensity (ton per thousand USD in 2010 prices)	Average	0.42	0.40	0.94	0.75
	Median	0.28	0.31	0.58	0.68
	Max	1.57	1.47	4.83	1.80
	Min	0.10	0.05	0.16	0.20

Note: the degree of decoupling is calculated based on the period 2015–2018, and the indexes in the table are for 2018. One country (Venezuela) does not have GDP data after 2015, so this table only shows 115 countries.

likely factors for absolute decoupling in these regions [89,90]. At the same time, economic growth of these developed countries was relatively weak, and expansion of demand was also slow.

Increasing international trade, accelerating global fragmentation, and expanding global value chains have been prevalent in recent decades. As a result, factors beyond a country's control, such as foreign emission intensity, foreign production structure, foreign consumption structure and volume, influence consumption-based emissions. Changes in foreign emission intensity were the second most important driver reducing consumption-based emissions in absolutely and relatively decoupled countries. They even exceeded the effects of domestic emission intensity as the largest factor to reduce consumption-based emissions in some countries showing no decoupling. Also, increasing demand for foreign products is the second largest factor to increase consumption-based emissions in countries with relative or no decoupling. These findings emphasize the need for supply chain management along the entire global supply chains and the importance of international collaboration for reducing consumption-based emissions.

Located downstream in global supply chains, developed countries (mostly in Western Europe and North America and mostly absolutely decoupled countries) tend to be net emission importers, i.e., EEI are larger than EEE [92]. Developing countries tend to be net emission exporters with higher PBE than CBE [32, 93], especially for Asia and Developing Pacific (see also **Fig. 2**). That is to say, there is a net emission transfer and outsourcing trend shifting production from developed to developing economies via global trade [70], mainly caused by cheap labor costs [93] and cheap raw materials [94]. Increasing openness to trade [95] and less stringent environmental legislation (acting as so-called pollution havens) [29,67,96] are also possible reasons. As a result, carbon leakage among countries has increased [95][32].

The net emissions transferred between developing and developed countries have slightly increased from 6.1% of global emissions in 1995 [58] to a peak of 7.3% in 2006 and then a subsequent decline [82]. One of the reasons for the decline was a decrease in the carbon intensity of traded products of about 40% between 1995 and 2015 [82]. Despite continual improvements, developing economies tend to have higher emission intensity than developed economies due to less efficient technologies and a carbon-intensive fuel mix [52,97].

Another reason for the decline in emissions transferred between developing and developed countries could be the shift of global trade as well as trade embodied emissions from Europe and the US to Asia. Asian exports in monetary units increased by 136% from 1996 to 2011, and its share of global exports increased from 27% to 48%, whereas Europe's share of global exports decreased from 51% in 1996 to 35% in 2011 [98]. Also, fast-growing Asian countries are catching up with traditional trade hubs (such as Russia and Germany) with fast growth in trade, especially with other countries of the global South [98]. As a result, developing countries are playing an increasingly important role in global trade. Emissions embodied in trade between developing countries, so-called South-South trade, have more than doubled between 2004 (0.47 Gt) and 2011 (1.11 Gt), which is seen as a reflection of a new phase of globalization [63]. Developing countries, therefore, have gained importance as global suppliers of goods and services and have also become more relevant as global consumers as they grow their domestic demand [95]. Since 2014, the CO_2 emission transfer between developing countries has plateaued and then slightly declined and seems to have stabilized at around the same level as between non-OECD and OECD countries at around 2.4 Gt CO_2 per year [82]. In both cases, a decrease in the carbon intensity of trade just about offset the increased trade volume [82].

Conclusions

Decoupling economic growth from greenhouse gas emissions and energy use is a precondition to stay within planetary boundaries. This study contributes to the exiting literature by investigating the extent of decoupling between economic growth and both production- and consumption-based CO_2 emissions in 116 countries; and revealing the driving factors behind such decoupling.

The results show that 32 countries (mainly developed ones) have absolute decoupling between GDP and production-based emissions in recent years (2015–2018). However, the decline in PBE could have been achieved via outsourcing of emissions to other countries. Our analysis shows that only 23 countries achieved absolute decoupling between GDP and consumption-based emissions. Another 67 countries (or 58%) have relatively decoupled, and 19 (or 16%) coupled economic growth with CBE. 6 countries were in an economic recession during the study period. We also observed that decoupling can be temporary, and decoupled countries may switch back to increasing emissions, which means that continuous efforts are needed to maintain decoupling. An analysis of driving factors shows that whether a country can achieve decoupling mainly depends on reducing emission intensity along domestic and import supply chains. This highlights the importance of decarbonizing supply chains and international collaboration in controlling emissions.

While there have been some achievements in decarbonizing global value chains these have been by far not sufficient as overall global emissions have continued to rise. Even though some countries have achieved absolute decoupling, they are still adding emissions to the atmosphere thus showing the limits of ‘green growth’ and the growth paradigm. Even if all countries decouple in absolute terms, this might still not be sufficient to avert dangerous climate change. Therfore, decoupling can only serve as one of the indicators and steps toward fully decarbonizing the economy and society.

Author contributions

K.H. and Y.S. designed the whole study. X.C. and K.F. conducted the structural decomposition analysis; Y.S. conducted the decoupling analysis. K.H. and Y.S. wrote the manuscript with inputs from T.W., X.C., and K.F.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at

Table S1 Decoupling of production-based emissions (PBE) and GDP of countries

Table S2 Decoupling of consumption-based emissions (CBE) and GDP of countries

Table S3 Sector classification of pricing data for GTAP MRIO tables.

Figure S1 Driving factors of consumption-based CO_2 emissions for absolute decoupling countries.

Figure S2 Driving factors of consumption-based CO_2 emissions for relative decoupling countries.

Figure S3 Driving factors of consumption-based CO_2 emissions for no decoupling countries.

Figure S4 Driving factors of consumption-based CO_2 emissions for economic recession countries.

Figure S5 Driving factors of consumption-based CO_2 emissions for various decoupling groups. Calculation based on GTAP MRIOs for 2004, 2007, 2011, and 2014 using the average of all possible first-order decomposition forms.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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