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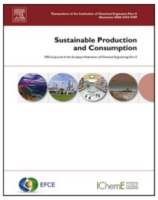

The influence of technology improvements and the consistency of environmental and economic indicators on decoupling of greenhouse gas emissions and economic growth

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ABSTRACT

Decoupling analysis examines the "green growth" of regions by assessing the relationship between their economy and resource use from both production and consumption perspectives. However, the effects of technology disparity and the consistency between environmental and economic indicators on regional decoupling degree, especially from the consumption perspective, remain unclear. This study re-visited the decoupling processes in forty-four economies between 2005 and 2015. "Technology-adjusted consumption-based GHG emissions" (TCBEs), instead of conventional CBEs, were quantified for decoupling analysis to reveal the impacts of technology disparity on decoupling results from the consumption perspective. We also incorporated the supply chain-wide value added of economies' final demand for consumption-perspective decoupling analysis. Results showed that economies with lower GHG intensities or more substantial reductions in GHG intensities exhibited higher decoupling degree. In other words, these economies were fully "credited" for their efforts in improving local production efficiencies. We also argued that using gross domestic product (GDP) as the economic indicator for quantifying decoupling degree from CBEs did not align with the consistency between environmental pressures and economic activities causing those pressures. By ensuring the consistency, decoupling degrees increased by 2–52 % for TCBEs and 1–19 % for CBEs. Our study raised a discussion on more accurate assessments of regional decoupling processes and enhances our understanding of the impact of technology disparity on global emissions.

1. Introduction

The concept of "decoupling", popularized by the Organisation for Economic Co-operation and Development, explores the relationship between economic growth and environmental pressures (OECD, 2002). Two types of decoupling, relative and absolute, are commonly recognized (UNEP, 2011). Relative decoupling occurs when resource use or environment pressures increase at a slower rate than the economic activity driving them, while absolute decoupling entails reductions in resource use or environmental pressures alongside continued economic growth. The debate on whether resource use (e.g., water consumption) or environmental pressures (e.g., carbon emissions) can be decoupled from economic growth has persisted over time. Evidence suggests that decoupling can be achieved at different geographic and sectoral levels. Wang and Su (2020) examined decoupling processes in 192 countries from 2000 to 2014 and found that developed countries like the United States (USA) and European countries have achieved relative decoupling and are progressing towards absolute decoupling, while many developing countries have not achieved decoupling. Similar comparisons between developed and developing countries have been conducted by Wu et al. (2018) and Hubacek et al. (2021). Decoupling processes have also been studied at finer scales such as cities (Chen et al., 2017; Shan et al., 2022; Wang et al., 2020), or within specific economic sectors such as agriculture (Luo et al., 2017) and iron and steel industry (Wang et al., 2020). Broader studies have applied the concept of decoupling to examine the relationship between various indicators, such as water use and thermoelectric power generation growth (Zhang et al., 2018), or environmental pressures and human well-being (IRP, 2019).

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The choice of accounting methods for regional environmental pressures can yield contrasting results in terms of decoupling. Discrepancy raises questions about the reliability of existing evidence on regional decoupling. Most studies calculated a decoupling index (see Eq. (12)) based on production-based emissions (PBEs) (Shan et al., 2022; Wang et al., 2020), which account for direct (or on-site) emissions from entities within a region (IPCC, 1996; Peters, 2008). PBEs include emissions associated with the production of exports but exclude emissions from imports. Relying solely on PBEs fails to capture the fact that high-income countries have shifted their carbon-intensive production overseas (López et al., 2013; López et al., 2018; Wang et al., 2023a), while their local consumers have increased demand for imported products (Davis and Caldeira, 2010; Li et al., 2021; Malik and Lan, 2016; Wang et al., 2023b). These production and consumption shifts have been contributing to increased emissions abroad. By neglecting these shifts via trade, high-income countries are more likely to exhibit decoupling, albeit at the expense of their trade partners. To address this issue in decoupling analysis, studies have also examined the decoupling of consumption-based emissions (CBEs) in various countries and regions. CBEs consider emissions throughout the entire supply chains that result from final demand of a region, regardless of where the products are produced (Barrett et al., 2013; Liu et al., 2015). CBEs are calculated by adding all import-related emissions and subtracting all export-related from a country's PBEs. This approach recognizes the importance of adopting a broader system boundary that extends beyond territorial emissions to avoid outsourcing of pollution. Hubacek et al. (2021) compared the extent of decoupling of 116 countries using both PBEs and CBEs and found that although countries' economic growth appeared to be decoupled from PBEs, it could be less decoupled or even no decoupled from CBEs.

A remaining question is whether CBEs accurately capture emission leakage via production and consumption shifts. However, literature has clearly shown that CBEs would incorrectly identify emission leakage that has never actually occurred (Jakob, 2021; Jiborn et al., 2018; Kander et al., 2015). This discrepancy arises because CBEs do not acknowledge countries' efforts in reducing the carbon intensity of their export sectors. For instance, when a country reduces the carbon content of its exports while trade patterns of the country and production structures in its trade partners remain unchanged (resulting in no change in import emissions), the net import emissions (emissions embodied in import minus emissions embodied in export) will increase. This would be considered as emission leakage, even though no additional leakage has occurred. On the other hand, the reduced export-related emissions would decrease the emissions attributed to import countries from the consumption perspective and could reduce the overall emissions globally. This decarbonizing process in the export has positive implications for the global climate, but it is not adequately reflected in conventional CBE accounting. A more appropriate accounting scheme has been proposed (Jakob, 2021; Jiborn et al., 2018; Kander et al., 2015) to address this issue, known as "technology-adjusted CBEs". This framework incorporates technology differences in export sectors within CBE accounting. It involves accounting for export-related emissions based on the global average emission intensity of the respective sector. In conventional CBEs, exports of carbon-free products would not change a country's CBE inventory relative to PBEs. However, in "technology-adjusted CBEs" accounting framework, exporters of carbon-free products can deduct emissions corresponding to the global average carbon intensity of producing such products from their CBE inventory. This adjustment acknowledges that their exports have avoided higher emissions that would have occurred during production elsewhere.

Building upon previous decoupling analysis between PBEs (and/or CBEs) from economic growth, this study extends the investigation by incorporating "technology-adjusted CBEs" to assess the impacts of technology disparity on decoupling results. Furthermore, we raise the discussion about the selection of economic indicators for decoupling analysis when different emission accounting methods are employed. Compared to emission indicators, economic indicators used in previous studies are in consistent as (price-adjusted) GDP (Chen et al., 2017; Haberl et al., 2020; Hubacek et al., 2021; Shan et al., 2022; Wang and Su, 2020; Ward et al., 2016). Yet the consistency between environmental pressures (from either the production or consumption perspective) and the economic activities causing those pressures are not always met. A simple example is using CBEs and GDP growth for decoupling analysis juxtaposes indicators from the consumption and production perspective, respectively. A more controversial case involved using material footprints of final consumption (a component of GDP) and overall GDP (comprising final consumption, fixed capital formation, and inventory changes) growth for decoupling analysis (Södersten et al., 2020). A delusion may be drawn for policy makers based on the improper choices of environmental and economic indicators for decoupling analysis. In summary, this study aims to examine how different choices of economic and emission indicators influence national decoupling results. We throw new light on the so-called "green growth" and improve our understanding of the impact of technology disparity on global emissions.

2. Methods

2.1. Multi-regional input-output modelling

Input-output (IO) modelling is applied in this study to trace GHG emissions of traded products through the supply chain. The IO model was developed by Leontief (1936), and has been widely used in consumption-based environmental impact assessments. The basic function lies in IO model is:

$$\mathbf{x} = \mathbf{Zi} + \mathbf{y} = \mathbf{Ax} + \mathbf{y} \tag{1}$$

where $\mathbf{x}$ is a column vector of total outputs, $\mathbf{Z}$ is a matrix of intermediate inputs, $\mathbf{y}$ is a column vector of final demand, $\mathbf{A}$ is a matrix of technical coefficients calculated by $\mathbf{Z}\hat{\mathbf{x}}^{-1}$ ("^" operator denoting diagonalization), $\mathbf{i}$ is a summation vector of appropriate length. In detail:

$$\begin{bmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \\ \ldots \\ \mathbf{x}^g \end{bmatrix} = \begin{bmatrix} \mathbf{Z}^{11}\ \mathbf{Z}^{12} \ldots \mathbf{Z}^{1g} \\ \mathbf{Z}^{21}\ \mathbf{Z}^{22} \ldots \mathbf{Z}^{2g} \\ \ldots\ldots\ldots\ldots \\ \mathbf{Z}^{g1}\ \mathbf{Z}^{g2} \ldots \mathbf{Z}^{gg} \end{bmatrix} \mathbf{i} + \begin{bmatrix} \sum_{r=1}^{g} \mathbf{y}^{1r} \\ \sum_{r=1}^{g} \mathbf{y}^{2r} \\ \ldots \\ \sum_{r=1}^{g} \mathbf{y}^{gr} \end{bmatrix}$$

$$= \begin{bmatrix} \mathbf{A}^{11}\ \mathbf{A}^{12} \ldots \mathbf{A}^{1g} \\ \mathbf{A}^{21}\ \mathbf{A}^{22} \ldots \mathbf{A}^{2g} \\ \ldots\ldots\ldots\ldots \\ \mathbf{A}^{g1}\ \mathbf{A}^{g2} \ldots \mathbf{A}^{gg} \end{bmatrix} \begin{bmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \\ \ldots \\ \mathbf{x}^g \end{bmatrix} + \begin{bmatrix} \sum_{r=1}^{g} \mathbf{y}^{1r} \\ \sum_{r=1}^{g} \mathbf{y}^{2r} \\ \ldots \\ \sum_{r=1}^{g} \mathbf{y}^{gr} \end{bmatrix} \tag{2}$$

where g is the total number of regions. Global multi-regional input-output (MRIO) tables are obtained from EXIOBASE 3.6 (Stadler et al., 2018). The global MRIO tables in EXIOBASE 3.6 involve forty-four individual economies and five aggregated regions between 1995 and 2015. 200 products are specified in the MRIO tables.

Eq. (1) can be converted into:

$$\mathbf{x} = (\mathbf{I}\text{–}\mathbf{A})^{-1}\mathbf{y} = \mathbf{Ly} \tag{3}$$

where $(\mathbf{I}\text{–}\mathbf{A})^{-1}$, i.e., $\mathbf{L}$, is the Leontief inverse matrix. The elements in $\mathbf{L}$ capture total (direct and upstream indirect) effects from a unit change in final demand.

GHG emissions of final demand are calculated as:

$$\mathrm{c} = \hat{\mathrm{s}}\mathrm{Ly} \tag{4}$$

In detail:

$$\begin{bmatrix} \mathbf{c}^{11}\ \mathbf{c}^{12}\ldots\mathbf{c}^{1g} \\ \mathbf{c}^{21}\ \mathbf{c}^{22}\ldots\mathbf{c}^{2g} \\ \ldots\ldots\ldots\ldots \\ \mathbf{c}^{g1}\ \mathbf{c}^{g2}\ldots\mathbf{c}^{gg} \end{bmatrix} = \begin{bmatrix} \mathbf{s}^{1}\ 0\ldots0 \\ 0\ \mathbf{s}^{2}\ldots0 \\ \ldots\ldots\ldots\ldots \\ 0\ 0\ldots\mathbf{s}^{g} \end{bmatrix} \times \begin{bmatrix} \mathbf{L}^{11}\ \mathbf{L}^{12}\ldots\mathbf{L}^{1g} \\ \mathbf{L}^{21}\ \mathbf{L}^{22}\ldots\mathbf{L}^{2g} \\ \ldots\ldots\ldots\ldots \\ \mathbf{L}^{g1}\ \mathbf{L}^{g2}\ldots\mathbf{L}^{gg} \end{bmatrix} \times \begin{bmatrix} \mathbf{y}^{11}\ \mathbf{y}^{12}\ldots\mathbf{y}^{1g} \\ \mathbf{y}^{21}\ \mathbf{y}^{22}\ldots\mathbf{y}^{2g} \\ \ldots\ldots\ldots\ldots \\ \mathbf{y}^{g1}\ \mathbf{y}^{g2}\ldots\mathbf{y}^{gg} \end{bmatrix} \tag{5}$$

where **s** is the row vector of direct GHG-emission coefficients (GHG emissions per unit of the output) for each sector and in each economy. **s** is also obtained from EXIOBASE 3.6. The GHG emission matrix $\mathbf{c}^{mn}$ captures emissions during the production process of final demand in country *m* which are consumed in country *n*.

The production-based emissions (PBEs) of country *m* are:

$$\mathrm{PBE}^{m} = \sum\nolimits_{n}^{g} c^{mn} \tag{6}$$

GHG emissions embodied in exports (CEX), and imports (CIM), of country *m* are:

$$\mathrm{CEX}^{m} = \sum\nolimits_{n\neq m}^{g} c^{mn} \tag{7}$$

$$\mathrm{CIM}^{m} = \sum\nolimits_{n\neq m}^{g} c^{nm} \tag{8}$$

The consumption-based emissions (CBEs) of country *m* are calculated by PBEs subtract (CEX-CIM). Here, CEX-CIM represents the balance of emissions embodied in trade (BEET):

$$CBE^{m} = \mathrm{PBE}^{m} - \overbrace{(\mathrm{CEX}^{m} - \mathrm{CIM}^{m})}^{\mathrm{BEET}^{m}} \tag{9}$$

2.2. Adjusting technology differences

"Technology-adjusted CBEs" (TCBE) is based on the conventional consumption-based emission accounting, but accounts export-related emissions using the global average of respective sector's emission intensity (Jakob, 2021; Jiborn et al., 2018; Kander et al., 2015). The global average GHG-emission coefficient of sector *i* (s_i^{glb}) is calculated as:

$$s_i^{glb} = \frac{\sum_{m=1}^{g} s_i^m x_i^m}{\sum_{m=1}^{g} x_i^m} \tag{10}$$

The technology-adjusted emissions embodied in exports ($TCEX^m$) are defined as the GHG emissions that *m*'s exports would cause if the same products had been produced with global average technology:

$$\mathrm{TCEX}^{m} = \sum\nolimits_{n\neq m}^{g} tc^{mn} \tag{11}$$

tc^{mn} is calculated in the same way as c^{mn}, except that country specific GHG-emission coefficients s_i^m are replaced by s_i^{glb}. Under the TCBE accounting framework, economies with higher production efficiencies than the global average would be "credited" with more GHG emissions of their export, while economies with lower production efficiencies would be "punished" with less GHG emissions of their export.

2.3. Decoupling analysis

The decoupling index (*DI*) of an economy *m* is calculated based on the changes of its economic indicators (*Ec_ind*) and GHG emissions (*Em_ind*), either from the production or consumption perspectives. In detail,

$$\begin{aligned} \mathrm{DI}^{m} &= \frac{\Delta \mathrm{Ec\_ind} - \Delta \mathrm{Em\_ind}}{\Delta \mathrm{Ec\_ind}} \\ &= 1 - \left(\frac{\mathrm{Em\_ind}_{t1} - \mathrm{Em\_ind}_{t0}}{\mathrm{Em\_ind}_{t0}} \middle/ \frac{\mathrm{Ec\_ind}_{t1} - \mathrm{Ec\_ind}_{t0}}{\mathrm{Ec\_ind}_{t0}} \right) \end{aligned} \tag{12}$$

Absolute decoupling refers to a decline of GHG emissions in absolute terms or as being stable while economic indicator grows (i.e., a decoupling index greater than or equal to 1); relative decoupling refers to the growth of emissions being lower than the growth of economic indicator (a decoupling index between 0 and 1); and no decoupling, which refers to a situation where GHG emissions grow to the same extent or faster than economic indicator (a decoupling index of less than 0).

This study also examines the influences of choosing different economic indicators (*Ec_ind*) on the decoupling results. *Ec_ind* is selected as: 1) GDP from the production perspective, while 2) supply chain-wide value added from the consumption perspective. GDP is a measure of a country's production, which includes its export and excludes the import, from the production perspective. The calculation of supply chain-wide value added (CB-VDs) is in the same way as the consumption-based emissions (CBEs) in Eqs. (5) and (9), by replacing direct GHG-emission coefficients (**s**) with direct value-added coefficients (**vd**) which represent direct added values when producing one-unit output of products.

3. Results

3.1. Factors influencing national GHG emissions: technology development and trade balance

Improvements in production efficiencies (represented by reductions in direct GHG intensities) in most economies indicated that production technologies have been enhanced during the period of 2005–2015. Thirty-three of the total forty-four individual economies have exhibited a decrease in direct GHG intensities (Fig. 1A). Notably, Malta and China achieved a substantial reduction of half their GHG emissions per unit of outputs. Other economies generally experienced an increase in GHG intensities, with Japan and Cyprus seeing over a 30 % increase between 1995 and 2015. The global average GHG intensity in 2015 was 0.3 kg CO_2 equivalent (simplified as kg hereon) per 2015 US$. Twelve individual economies had higher GHG intensities than the global average in that year. Encouragingly, eight of these economies, including China, Russia, and India, managed to reduce their GHG intensities throughout the study period. Differences between GHG intensities of exports and imports further reflected disparities in technology levels between economies and their trade partners (Fig. 1B). In detail, economies with higher GHG intensities than the global average displayed higher intensities in their export but lower intensities in their import, and vice versa. The largest disparity in GHG intensities between exports and imports was found in South Africa, where the difference exceeded fourfold (2.7 kg per export versus 0.5 kg per import). The discrepancy can be attributed to the product categories of South Africa's export and import. Import activities predominantly comprised service-related products like financial services, computer and business services, accounting for around 40 % of its total import in 2015. Conversely, export activities primarily involved metal and non-metallic mineral products, as well as machinery and equipment, accounting for 30 % of its total export. Other economies with relatively higher GHG intensities in exports than imports included Russia, China, and India. In contrast, most developed economies such as the United Kingdom, Switzerland, Germany, and the United States (USA) showed relatively larger GHG intensities in their imports compared to their exports.

Economies with higher GHG intensities than the global average indicate that their technology-adjusted CBEs (TCBEs) would be larger than their conventional CBEs, according to Eq. (9). This is because, under the TCBE accounting framework, producing the same amount of exported products in these economies would result in higher GHG emissions compared to producing the exported products using global average technology levels. This disparity is precisely reflected in the balance of GHG emissions embodied in trade (BEET, Fig. 1C)–the net export of GHG emissions embodied in trade (*CEX-CIM*, Eq. (9)). In other words, under the TCBE accounting framework, economies with higher domestic GHG intensities of production would be "punished" by lower GHG emissions embodied in exports, and hence have lower BEET but larger TCBEs (calculated by PBE − BEET). In this context, South Africa, India, Indonesia, and Russia showed substantial increases in their consumption-based GHG emissions from conventional CBEs to TCBEs. In contrast, economies with lower GHG intensities than the global average,

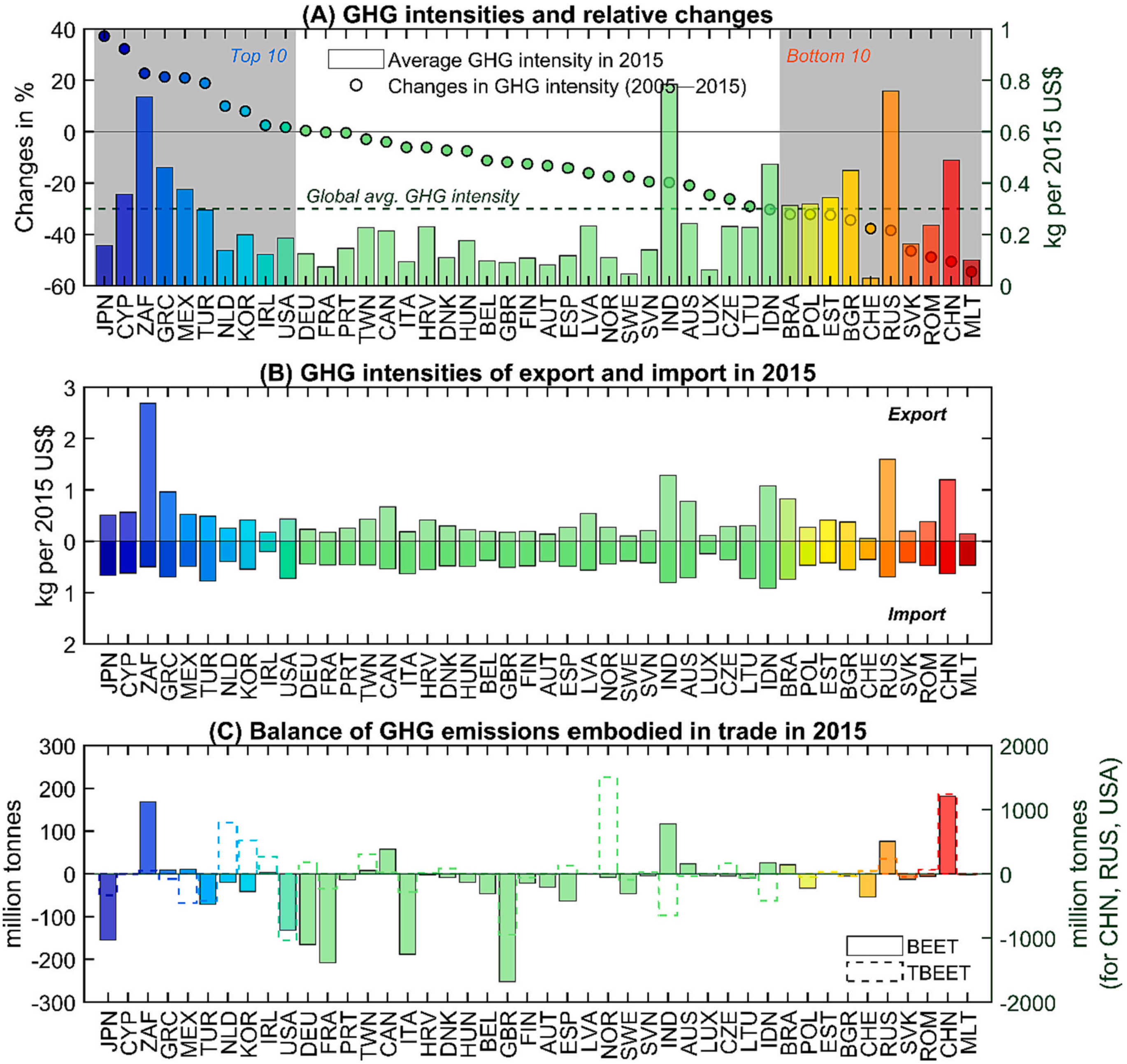

Fig. 1. Greenhouse gas (GHG) emission intensities and balance of GHG emissions embodied in trade (BEET) in forty-four individual economies. The top and bottom ten economies of GHG intensities are highlighted. In C, the BEET and technology-adjusted BEET (TBEET) of China, Russia, and United States should be referred to the right y-axis. Full names of all the economies can be found in Table S1.

such as Norway, Netherlands, and South Korea, would be "credited" in terms of consumption-based emissions under the TCBE accounting framework for their efforts on improving domestic production efficiencies. The USA is an exception due to its relatively low GHG intensity but larger net import of GHG emissions (indicating it is "punished") under the TCBE accounting framework. The USA exception was also observed in the study by Kander et al. (2015) for the year 2009. The trade specialization of USA can explain this exception, as it has been outsourcing its emissions to the rest of the world through importing emission intensive and low value-added products (Jakob and Marschinski, 2012; Kander et al., 2015). In fact, these imports contributed 43 % to USA's GHG imports in 2009.

3.2. Decoupling stories under different GHG-emission accounting methods

Our study further confirmed that choosing different GHG-emission accounting methods can yield quite different decoupling results between GHG emissions and GDP in the same economy. Additionally, apart from accounting methods, economies' decoupling degrees can change over time. Fig. 2 illustrates the trends of PBEs, CBEs, TCBEs, and GDP of individual economies covered in EXIOBASE 3. We examined the decoupling results for these economies during the two distinct time periods: 2005–2010 and 2010–2015. Detailed *DI* values of economies are listed in Table S1, Supplementary Information. More economies achieved decoupling (either absolute or relative) during the period of 2005–2010 compared to 2010–2015. Fifteen of the total forty-four individual economies achieved absolute decoupling from both PBEs and CBEs during 2005–2010, whereas only eight economies achieved

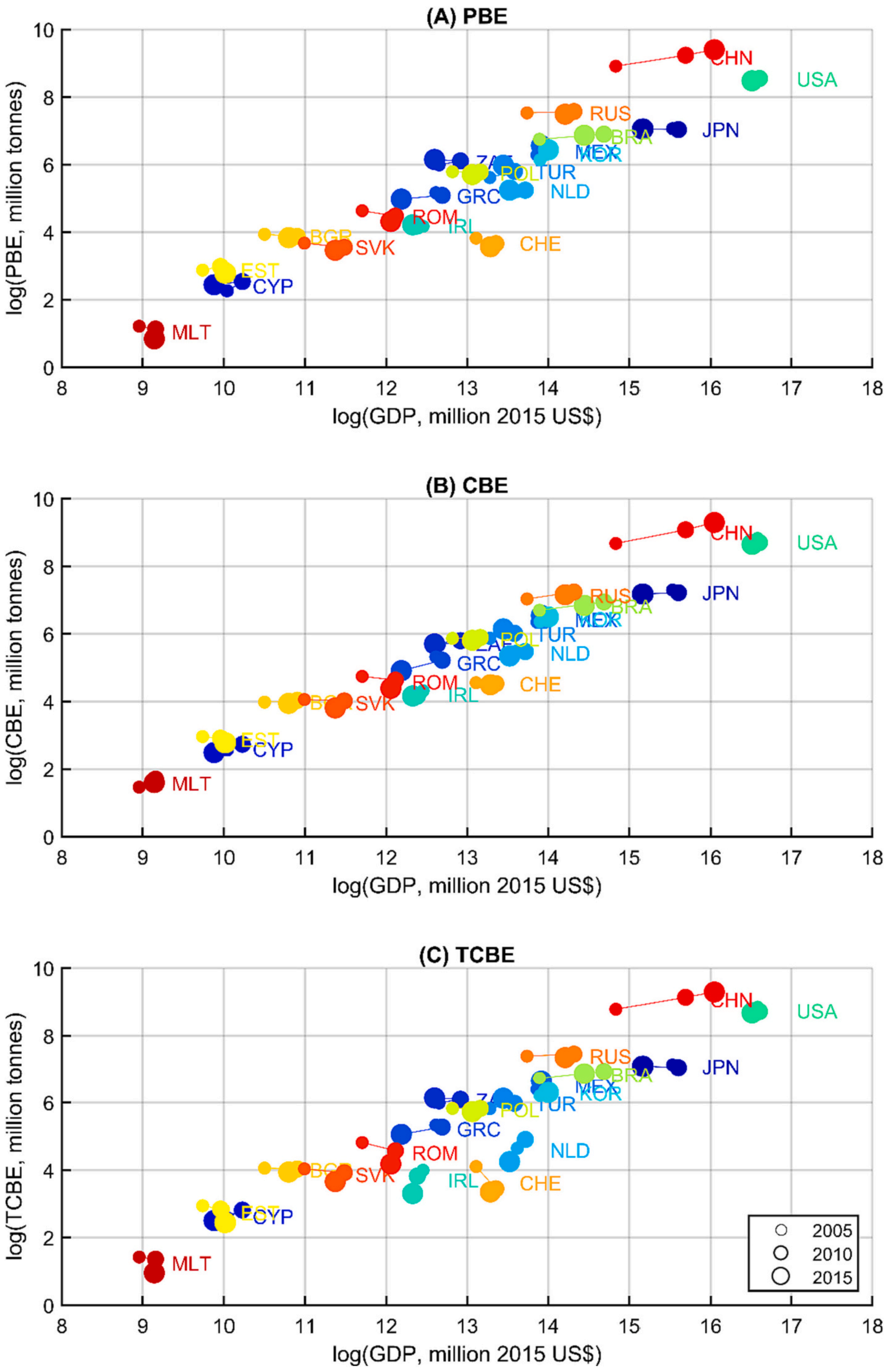

Fig. 2. Trends of greenhouse gas (GHG) emissions and GDP in years 2005, 2010, and 2015. The Y-axis represents the 10-logarithm of (A) production-based emissions (PBE), (B) consumption-based emissions (CBE), and (C) technology-adapted CBE (TCBE). The X-axis shows the 10-logarithm of GDP. Economies in color dots are same to the economies highlighted in Fig. 1, that is, the top 10 and bottom 10 economies in term of GHG intensity changes between 2005 and 2015. Full names of all the economies can be found in Table S1.

absolute decoupling during 2010–2015. As described in the Introduction, a common pattern is known as developed countries through outsourcing GHG emissions to achieve lower PBEs and higher decoupling degrees. This pattern was observed in economies such as Japan, Canada, Norway, Austria, Germany, and Cyprus, which all showed lower decoupling degree from CBEs compared to PBEs. When accounting GHG emissions under the TCBE framework, more economies achieved absolute decoupling of TCBEs and GDP during the two periods, compared to conventional CBEs. This can be attributed to the general improvement in production efficiencies across economies during the study period. Furthermore, the economies covered in EXIOBASE are mostly European and developed countries, and developing countries like China and Brazil which have already achieved relative higher production efficiencies compared to the global average (Fig. 1A). In addition to accounting methods, our study confirms the finding from Hubacek et al. (2021) that the degree of decoupling in economies can change over time. For instance, USA showed absolute decoupling from all the PBEs, CBEs, and TCBEs during 2005–2010, but only relative decoupling during 2010–2015. Cyrus showed no decoupling from all the PBEs, CBEs, and TCBEs during 2005–2010, but achieved relative decoupling during 2010–2015.

Our results also found a strong correlation between decoupling degrees of economies and their domestic production efficiencies (represented by GHG intensities, Figs. 3 and S1), especially in economies that achieved the largest reductions in GHG intensities during 2005–2015. Here we examine the overall changes in decoupling degrees from PBEs

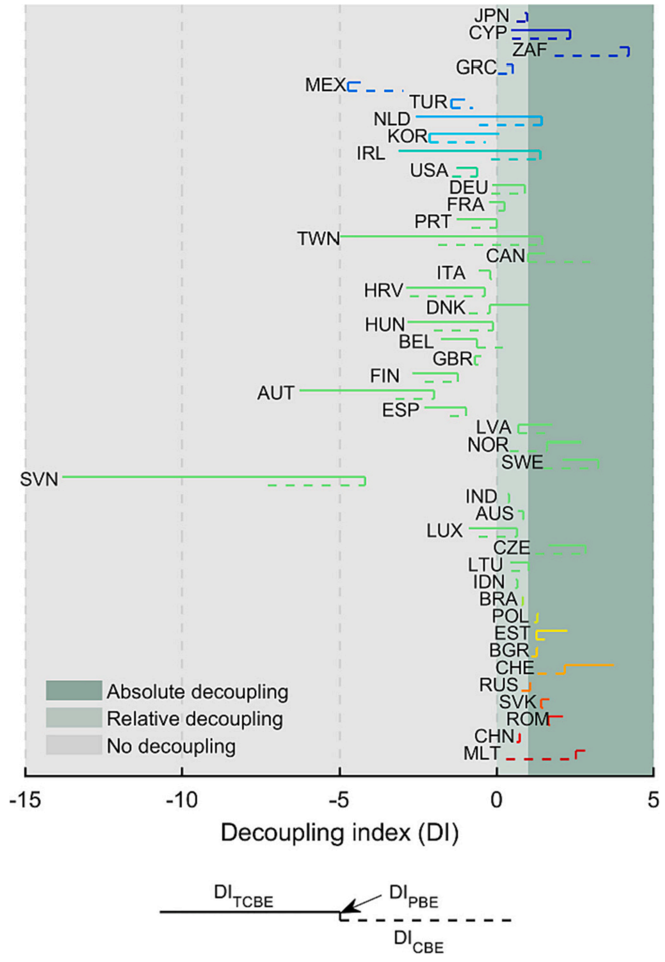

Fig. 3. Changes in decoupling index (DI) of 44 individual economies in 2015 by using different accounting methods of greenhouse gas (GHG) emissions. The idea of this chart was referred to Kander et al. (2015). Full names of all the economies can be found in Table S1.

to CBEs and TCBEs during the entire study period (2005–2015). Top ten economies with the largest reduction in GHG intensities (Fig. 1A) all achieved decoupling (either absolute or relative decoupling) from PBEs, CBEs, and TCBEs. It is important to note that China and Brazil only achieved relative decoupling from PBEs, CBEs, and TCBEs during the study period. The correlation coefficients (at a 10 % significance level) between decoupling indices (*DIs*, using PBEs, CBEs, and TCBEs) and GHG intensities of these economies were −0.72, −0.23, and −0.74, respectively. In contrast, among the top ten economies with the smallest reductions in their GHG intensities, only three economies (Cyprus, Ireland, and Netherlands) achieved absolute decoupling between PBEs and GDP, and no economies achieved absolute decoupling from CBEs and TCBEs. Netherlands and Ireland showed the substantial changes in decoupling results from PBEs (absolute decoupling) to CBEs and TCBEs (no decoupling). This shift was primarily influenced by economic recession, as shown in Fig. 2. The correlation coefficients (at a 10 % significance level) between decoupling indices (*DIs*, using PBEs, CBEs, and TCBEs) and GHG intensities of these economies were 0.31, 0.39, and 0.61, respectively. Lastly, when GHG emissions are accounted for as TCBEs, economies with lower GHG intensities (e.g., Japan, Norway, Sweden) or greater reduction in GHG intensities (e.g., Switzerland, Estonia, Russia) are also credited in their decoupling degrees. Higher decoupling degree from TCBEs, compared to CBEs, has been found in these economies.

3.3. Changes in decoupling degree due to choosing different economic indicators

Taking the top and bottom ten economies (Fig. 1) as examples, this study showed that ensuring the consistency between environmental and economic indicators resulted in higher decoupling degree (Table 1), especially in economies with the largest reductions in GHG intensities during the study period. Decoupling results between PBEs and GDP would not change, since both indicators are already from the production perspective. From the consumption perspective (CBEs or TCBEs), the decoupling degree in most selected economies remained the same regardless using GDP or CB-VD as the economic indicator for decoupling analysis. Nevertheless, the decoupling indices of most selected economies increased when using CB-VD for decoupling analysis. This increase was particularly prominent in economies with the largest reductions in GHG intensities, where all the decoupling indices increased when CB-VD was used instead of GDP. A wider range of increase was found in decoupling results from TCBEs (2–52 %), compared to CBEs (1–19 %). No consistent increase or decrease was found in DIs of the other ten economies by using CB-VD instead of GDP for decoupling analysis. However, substantial changes in the decoupling degree of economies by using CB-VD instead of GDP still existed. Examples are Ireland changed its decoupling degree from no decoupling to relative decoupling when using CB-VD for decoupling analysis with CBEs, while South Korea changed its decoupling degree from relative decoupling to no decoupling when using CB-VD for decoupling analysis with TCBEs.

CB-VD represents the total value added along the entire supply chain of one certain economy's final demand (details see Section 2.3). The interpretation of CB-VDs is not as straightforward as CBEs. CBEs are used to allocate emission burdens along the entire supply chain, assigning responsibility from the producers to consumers (Barrett et al., 2013; Liu et al., 2015). As economic benefits, the assignment of value added from the producers to consumers is not related to the economic responsibilities, rather being regarded as economic values created along the supply chain. The created economic values along the supply chain can also be attributable to the final consumption of an economy, i.e., from the consumption perspective. We can see the controversy of CB-VDs in terms of its practical meaning. As such, this study only theoretically conducts the decoupling analysis between GHG emissions and GDP or CB-VDs. We tend to show how the choices of different economic indicators influence national decoupling results, and avoid a delusion to be drawn for policy makers based on improper environmental and economic indicators for decoupling analysis.

4. Discussion

Decoupling analysis has been widely used for assessing the “green growth” of regions between economy and resource use (Hickel and Kallis, 2019; Hubacek et al., 2021; OECD, 2002; Shan et al., 2022). This study re-visited the decoupling processes in forty-four individual economies covered in EXIOBASE 3. We analyzed the influences of choosing different accounting methods for environmental and economic indicators on regional decoupling degree. Firstly, the “technology-adjusted consumption-based GHG emissions” (TCBEs) are used for decoupling analysis to reveal the impacts of technology disparity on decoupling results from the consumption perspective. TCBEs addressed the limitation of conventional CBE accounting–may incorrectly identify emission leakage that has never been actually generated–by crediting economies for cleaning up their export sectors (Jiborn et al., 2018; Kander et al., 2015). Secondly, this study also analyzed the influences of the consistency between environmental and economic indicators on the decoupling results. We argued that using the common economic indicator–GDP–to quantify decoupling degree from consumption-based emissions didn't meet the consistency between environmental and economic indicators, both of which should be from the consumption perspective. We used the supply chain-wide value added of economies'

Table 1

Decoupling index (DI) using different accounting methods of greenhouse gas (GHG) emissions and value added during the period of 2005–2015. Cells in dark green, light green, and grey represent absolute, relative, and no decoupling, respectively. Decoupling results of all regions are listed in Table S2, Supplementary Information.

	PBE	**CBE**		**TCBE**	
	GDP	GDP	CB-VD	GDP	CB-VD
Top 10 in Figure 1					
Japan	0.97	0.63	0.59	0.88	0.87
Cyprus	2.34	0.48	0.48	0.46	0.46
South Africa	4.21	1.84	1.84	3.92	3.90
Greece	0.51	0.04	0.12	0.31	0.36
Mexico	-4.74	-2.98	-4.93	-4.33	-6.95
Turkey	-1.44	-0.76	-0.58	-1.01	-0.81
Netherlands	1.43	-0.57	-0.24	-2.58	-1.83
South Korea	-2.14	-0.35	-0.63	0.08	-0.10
Ireland	1.38	-0.18	0.22	-3.13	-1.72
USA	-0.63	-1.42	-0.94	-1.29	-0.83
Bottom 10 in Figure 1					
Brazil	0.83	0.79	0.80	0.81	0.83
Poland	1.29	1.19	1.22	1.33	1.38
Estonia	1.26	1.53	1.82	2.25	2.93
Bulgaria	1.27	1.10	1.22	1.32	1.68
Switzerland	2.17	1.30	1.43	3.73	4.95
Russia	1.06	0.78	0.79	1.07	1.07
Slovakia	1.41	1.48	1.61	1.68	1.86
Romania	1.64	1.70	1.98	2.11	2.56
China	0.73	0.63	0.65	0.72	0.73
Malta	2.52	0.29	-0.28	2.82	4.28

final demand instead of GDP for consumption-perspective decoupling analysis. Results showed that economies with lower GHG intensities or more significant reductions in GHG intensities demonstrated higher decoupling degree under the analysis framework developed in this study. In other words, economies with lower GHG intensities or substantial reductions in GHG intensities will be fully credited for their efforts on improving local production efficiencies. This approach can serve as an incentive for countries to continually improve production efficiencies rather than simply outsourcing their resource-intensive industries to other countries. Our study raised the discussion about how to assess the decoupling processes of regions more accurately and improved our understanding of the impact of technology disparity on global emissions.

Less GHG emitting technologies have the potential to enable the decoupling of economies from carbon-intensive activities. Particularly in the energy sector, renewable energy sources like solar, wind, and hydropower have gained significant momentum due to their ability to generate electricity without releasing GHG emissions (Yang et al., 2022). By transitioning to renewable energy sources and adopting energy-efficient practices, countries can reduce their reliance on fossil fuels and decrease carbon emissions while maintaining economic growth. Moreover, the widespread adoption of electric vehicles in transportation sector and sustainable agricultural practices like precision farming, organic agriculture, and agroforestry can further contribute to decoupling by reducing emissions from transportation and land use. However, it is important to acknowledge that the decoupling process requires comprehensive policy frameworks, technological advancements, and international collaboration to ensure a just transition and maximize the benefits of these less GHG emitting technologies.

Choosing which economic indicator for decoupling analysis is rarely discussed in previous studies. Typically, GDP is commonly used as the economic indicator, which is clarified as an indicator from the production perspective (see Section 2.3). This study used the consumption-based value added (CB-VD), which is exactly from the consumption perspective, for decoupling analysis from regional CBEs and TCBEs. The values of DIs between CBEs (or TCBEs) and CB-VD indicate production efficiencies from a broader system, i.e., encompassing the entire supply chain. The associated decoupling results therefore present the “green growth” of the supply chain. It is important to note that not all cases of emission displacement across countries are detrimental to the global climate. The key lies in optimizing the supply chain and minimize the (in)direct emission along the chain. If countries with higher carbon intensive energy and production technologies than the world average specialize in reducing exports of GHG-intensive commodities and instead import such commodities, it can contribute positively to the climate. In this context, countries may as well specialize their trade according to comparative advantages of resources and emissions (Atkinson et al., 2011; Su and Thomson, 2016). This underscores the significance of supply chain management along global supply chains and the need for synergistic collaboration and action on reducing emissions at the supply chain level.

Studies have also investigated decoupling processes of sectors (Karmellos et al., 2021; Luo et al., 2017; Wang et al., 2020). While previous studies predominantly examined sectoral decoupling from the production perspective (i.e., using direct emissions and GDP growth), our decoupling analysis framework offers a broader perspective that encompasses the entire supply chain of production inputs. This broader approach can assist sectors in re-evaluating their decoupling processes. Taking agriculture as an example, studies tended to quantify direct emissions of agricultural activities from emission sources such as fertilizer, pesticide, crop residues, and feed intake (IPCC, 2019). The consistency between environmental and economic indicators is not satisfied when involving crop products for animal farming in the calculation of total agricultural emissions. Crop residues and feed intake accounted for around 20 % of GHG emissions from livestock supply chains (Gerber et al., 2013), which are main emission sources in agricultural activities.

Yet, a double accounting occurs in the conventional emission accounting approach for the agricultural sector. Emissions from animal-farming-used crops are counted both in crop growing (from the production perspective) and in animal farming due to using the crops (from the consumption perspective). When assessing the decoupling of agriculture along the entire supply chain, measures to reduce the supply chain-wide emissions can include substituting emission-intensive upstream inputs with less emission-intensive products, such as using organic fertilizer. Technology developments are crucial for certain sectors such as renewable energy facilities, carbon capture and storage in heavy industries, and irrigation technologies for crop growing. These technological developments are necessary to reduce the production-side and supply chain-wide resource consumption and emissions for sector-level decoupling processes.

This study has several limitations. The main limitation lies in the uncertainty of the EXIOBASE 3 database (Stadler et al., 2018). The MRIO tables and the GHG inventories are compiled in EXIOBASE 3 and directly used in this study. As such, uncertainty inherent in the raw data used in EXIOBASE 3 it not fully recognized or incorporated into the decoupling analysis framework. Secondly, although this study analyzed the influences from 1) technology improvement and 2) the consistency between environmental and economic indicators for decoupling analysis, it does not delve into the underlying factors driving the decoupling results. These underlying factors can be partially understood through decomposition analysis, as demonstrated in studies Hubacek et al. (2021), Shan et al. (2022), and Karmellos et al. (2021). Revealing the drivers behind the decoupling results is helpful for applying factor-specific measures to improve economies' decoupling process. But it is not the main research line of this study. Thirdly, one may argue that using global average GHG-emission coefficients of sectors are not representative enough for technology-level differences among countries. Alternatively, weighted average emission factors, which are at the process basis, can be used to determine the emission behavior of specific systems. The choices of global average GHG-emission coefficients of sectors or process-based emission factors actually reflect the long-lasting debates about using process-based or IO table-based approach in assessing environmental impacts. Developing a hybrid model, such as hybrid supply and use modelling, that combines both approaches could be a promising avenue for future research. Lastly, in conventional IO modelling, the requirements of durable capital assets in economic production are not included. This results in underestimations of GHG emissions (Ye et al., 2021; Ye et al., 2023). Despite whether or not the consistency of environmental and economic indicators is met, studies did show that the decoupling degrees of economies would fundamentally change when considering the capital-related environmental pressures (Södersten et al., 2020). In the future research, it is important to comprehensively capture the requirements of all the resource and economic inputs at the production processes or along the supply chains for decoupling analysis.

5. Conclusions

This study delved into the decoupling processes of forty-four individual economies and five aggregated regions, leveraging the comprehensive EXIOBASE 3 database. Results demonstrated that economies with less GHG intensities or more significant reductions in GHG intensities exhibited higher decoupling degree within the analysis framework developed in this study. This highlights the potential of adopting and scaling up less GHG emitting technologies, such as renewable energy sources, electric vehicles, and sustainable agricultural practices, in economic systems to facilitate decoupling. Additionally, when "technology-adjusted consumption-based GHG emissions" (TCBEs) were used for decoupling analysis, this study found that more economies achieved absolute decoupling between TCBEs and GDP over the study period. This finding underscores the importance of considering technology improvements and their impacts on emissions when formulating climate mitigation policies. Cost-benefit analysis between investment requirements on mitigation technologies and potential in reducing GHG emissions is called to provide a more comprehensive picture for policy makers (IPCC, 2022). Moreover, this study revealed that economies with the most substantial reductions in GHG intensities had higher correlation coefficients between decoupling indices (*DIs*) and GHG intensities. This highlights the potential for policy interventions and other economic-environmental-social factors to drive emissions reductions and enhance decoupling efforts. It is also important for future research to address the limitations identified, such as uncertainties in data sources and the need for a comprehensive understanding of the underlying drivers of decoupling processes. Policymakers can leverage these findings to design and implement robust climate change policies that incentivize the adoption of less GHG emitting technologies, foster sustainable economic growth, and promote decoupling between emissions and economic activities.

Declaration of competing interest

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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Appendix A. Supplementary data

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