Examining the role of BRICS countries at the global economic and environmental resources nexus

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Abstract: The BRICS countries (Brazil, Russia, India, China and South Africa) are central to future global economic development. However, they are facing both environmental and natural resource stresses due to their rapid economic growth. This study examines the balance between economic benefits and cost of environmental emissions and resource usage in BRICS countries so that future sustainable development insights can be provided. The historical trends of carbon dioxide (CO_2), sulfur dioxide (SO_2), water, land, energy and material footprints of these countries from 1995 to 2015 are evaluated with a multi-regional input-output model. Also, whether a decoupling relationship exists between economic development, environmental emissions and resources consumption, is examined. In addition, whether environmental emissions and resource usage costs to obtain identical economic gains of these countries in global trade are explored. The major results show that in congruence with economic development, the average annual growth rates of footprint indicators ranged from 0.2% in 1995 to 9.8% in 2015. A decoupling effect did not occur for CO_2 emissions or water consumption but did exist for other indicators. Global trade across the supply chain shows to achieve a unit of USD economic benefit from trade, BRICS countries tend to use relatively greater environmental emissions and resource consumption to high income countries, when compared to other income level countries. These emergent economies did receive relatively greater benefits per environmental emissions and resource usage cost from lower-middle and low-income countries.

Key words: footprint; virtual trade; decoupling; cost-benefit; BRICS countries; governance

1 Introduction

The BRICS countries – Brazil, Russia, India, China, and South Africa – are significant players in recent global economic development; they also have had profound environmental and natural resources influences in recent decades (Siddiqui, 2016; Wu et al., 2017). Their aggregated GDP over the global GDP (in 2011 international dollars) – increased from 17.6% in 1995 to 32.5% in 2018[1]. By 2050 it is projected that China and India will become the first and third largest economies in the world, while Russia and Brazil will rank the fifth and sixth, respectively, behind Japan (Pieterse, 2012; Siddiqui, 2016). With more than 40 percent of the global population and nearly 30 percent of the land mass in the world, the BRICS countries are facing several environmental and resource consumption issues. These issues have – to an extent – arisen from rapid development of globalization and urbanization (Wiedmann et al., 2015; Yang et al., 2017; Zhang et al., 2018; Zheng et al., 2018). For example, the BRICS countries emitted more than 40% of global CO_2 emissions in 2013 (Liu et al., 2017a). South Africa is the world's 14th largest emitter of greenhouse gases in 2018, its CO_2 emissions will increase to 90% above 1990 levels by 2030, excluding land use and forestry – land use, land-use change and forestry – due to its higher economic growth[2] .Brazil was the 13th largest CO_2 emitter in 2016. Russia's economic development also induced high CO_2 emissions and it is currently among the top 5 emitters (Yang et al., 2017). India's CO_2 emissions are also expected to increase rapidly and continuously in the future; it is currently the third largest emitter (Anandarajah and Gambhir, 2014). As the "world's manufacturing factory", China is the largest CO_2 emitter country in the world (Jiang et al., 2019).

Natural resource consumption is also a major concern. Non-renewable energy consumption of BRICS countries accounted for more than 35% of the global total in 2013 (Liu et al., 2017a). From 1970 to 2010 global metal ore extraction tripled to 7.4 billion tons, in which 54% was used in the five BRICS countries (Zheng et al., 2018).

[1] https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.KD
[2] https://www.carbonbrief.org/the-carbon-brief-profile-south-africa

BRICS countries, especially China and India, are expected to use more natural resources in the future. China and India will account for half of global energy use growth through 2035 (Bond, 2015).

Rapid global economic development and maturing global supply chains have caused greater international trade. International trade plays a key role in shifting consumed commodities. This situation has meant greater embodied flows – carbon emissions, air pollutant emissions, virtual land, and embodied energy – transferred between countries (Tian et al., 2018b). For instance, over the past fifty years NO_X and SO_2 emissions footprints of developed countries have shifted to developing countries (Kanemoto et al., 2014). US consumption was shown to exert threats to terrestrial biodiversity in southern Brazil and to marine species in Southeast Asia across the global supply chain trade (Lenzen et al., 2012). These linked influences require that countries consider the environmental emissions and resource consumption issues along the global supply chain in trade; rather than just domestic production. These considerations are necessary to holistically understand economic development and environmental and resource concerns (Davis and Caldeira, 2010; Kan et al., 2019b).

Under such circumstances, we propose three scientific questions. (1) What are the time series trends of BRICS countries' environmental emissions and resources usage? (2) What are the relationships between BRICS countries' economic development and environmental emissions and resources usage over time? (3) In order to obtain identical national economic benefits, what are their costs from environmental emissions and resources usage using a consumption-based perspective for international trade across the global supply chain?

In order to address the research questions and goals while building on – filling gaps of – previous studies (see Section 2 Background and Literature), we evaluate environmental (CO_2 and SO_2) and resources (water, energy, land, material) indicators. These six indicators are used to identify BRICS country footprints using multi-regional input-output data from 1995 to 2015.

We examine the relationship between BRICS countries' economic development and environmental emissions and resources consumption from a decoupling analysis perspective. We evaluate BRICS country environmental and resources cost to obtain identical economic gains from their involvement in global supply chains through integrated trade indicators. The major contribution of our study is to reveal the imbalance in relationships between economic development and environmental emissions and resources usage issues systematically from a consumption-based perspective. Our results provide insights for developing countries' future sustainable development.

The whole paper is organized as follows. Section 2 provides a literature and background review further identifying the gaps in the literature. It also sets a foundation for this study. In section 3 methods and data sources description are provided. Section 4 presents major study results related to the proposed research questions. Section 5 provides a related discussion and policy implications. The final section provides a conclusion, limitations discussion, and future research discussion.

2 Background and Literature

Consumption-based accounting differs from production-based accounting. Production based accounting determines the domestic environmental and resources usage. Consumption-based accounting seeks to reveal the extent a country relies on global environmental emissions and resource consumption – both domestic and globally – to support its final consumption (Hertwich and Peters, 2009; Davis and Caldeira, 2010). Consumption-based accounting reflects the total environmental and resource impacts across the full global supply chain in order to satisfy a single country's economic activities. These accounting measures can help evaluate country level international trade.

Recent environmental emissions and resource usage studies have explored global (Hertwich and Peters, 2009), national (Tian et al., 2018c), and provincial (Wu et al., 2019a) levels. These trade studies have investigated shifting patterns of various embedded flows such as carbon emissions (Davis and Caldeira, 2010), water (Tian et al., 2018c), land (Bruckner et al., 2015), energy (Tian et al., 2019b), and material (Bruckner et al., 2012) flows. In this section, two streams of literature inform this study. The first stream relates to tradeoffs between economic development and environmental emissions and resource usage outcomes in BRICS countries. The second stream of literature focuses on environmental and resource issues in global trade using a consumption perspective, especially in BRICS countries. With the help of these two streams of literature, the gaps between our current study and previous studies are explored.

2.1 Economic development and environmental and resources relationships

The preponderance of the literature investigates economic development and environmental emissions and resources usage relationships in BRICS countries with a production-based rather than a consumption-based approach. Studies with the production-based perspective have predominantly been driven by climate change concerns (Yu et al., 2014; Wang et al., 2016; Yang et al., 2017). Table A1 in our Supporting Information (SI) summarizes major consumption-based studies exploring economic development and environmental and resources relationships.

The majority of previous studies explored the economic development and environmental and resources relationship from a *partial* consumption perspective. The difference between production-based, partial consumption-based and full consumption-based perspectives is shown in Figure A1 in SI. Few studies explored the topics of our study from a global supply chain perspective. Most studies identified the relationship between BRICS country economic development and carbon emission issues; few studies focused on other resource indicators, such as energy, material and metal (Wiedmann et al., 2015; Schandl et al., 2016; Kan et al., 2019a). Of these topics, China – as a country – is the most studied. Other BRICS countries still require further investigation. To address these gaps, our study will investigate environmental (CO_2 and SO_2) and resources (water, energy, land, material) indicators to explore economic development with environmental and resource relationships from 1995 to 2015 using a full supply chain consumption perspective in BRICS countries.

2.2 Consumption-based impacts from BRICS country international trade

International trade can play a significant role in environmental and resource redistribution. This global redistribution can occur through traded commodities, which may contain large volumes of embodied upstream environmental emissions and resources consumption across the supply chain. Such redistribution can cause environmental and resource issues in developing and underdeveloped countries (Tian et al., 2018b). Several previous consumption-based studies in BRICS countries show that household consumption is a major cause of BRICS countries carbon footprints (Hertwich and Peters, 2009). The increasing exports of embodied CO_2 and virtual water from China, India and Brazil is to meet final consumption demands in the USA and EU countries (Liu et al., 2017b). China represents 22.5% of all global CO_2 emissions from trade; mostly to satisfy trade partner consumption (Davis and Caldeira, 2010). It has also been found that Russia was a major net water importer, in contrast to China and India who were the leading net water exporters (Wu et al., 2019b). Japan and Germany 'outsourced' their pollution to BRIC countries (Zhao et al., 2019).

Table A2 in SI describes trade related issues of BRICS countries. Previous studies show that environmental emissions and resources usage issues in China are well investigated. Other BRICS countries related investigations are fragmentized, especially studies concerning South Africa. The majority of footprint indicator studies focus on CO_2 emissions and water. Other environmental emissions and resources usage indicators – for example, land, energy and material footprints – still need systematic evaluation. Most previous studies consider single year and older time series results. The majority studies identifying environmental emissions and resources usage concerns are separate from their link to economic dimensions. Few studies explored the imbalanced relationship between economy and environment and resources of BRICS countries global trade (Duan and Jiang, 2017; Zhang et al., 2018). The relationship between economy and, environment and resources, is important for a country's sustainable economic development and management of environment and resources. Given this context, our current study tries to identify the macro trend of BRICS countries across their global supply chains which link economic development with environmental emissions and resource usage.

3 Method and Data Sources

3.1 Multi-Regional Input-Output (MRIO)

A MRIO model is utilized in order to trace BRICS country global supply chain footprints over time. MRIO can effectively determine consumption-based environmental emissions and resources usage issues. It also allows for an exploration of the complex relationships between regions, economic sectors and final demand (Giljum, 2013).

Footprint indicators based on MRIO can inform country environmental emissions and resources usage and economic development relationships in addition to identifying embodied impacts across the supply chain (Tukker et al., 2016).

The standard MRIO expression is shown in equation (1).

$$X^{r} = C^{rr} + Y^{rr} + \sum_{s\neq r} L^{rs} = B^{rr}X^{r} + Y^{rr} + \sum_{s\neq r} B^{rs}X^{s} + \sum_{s\neq r} Y^{rs} \tag{1}$$

Where, X^r is the total output vector in region r; matrix C^{rr} is domestic intermediate consumption in region r. Domestic final consumption – households, governments and gross fixed capital formation – is represented by vector Y^{rr}. Parameter L^{rs} is bilateral trade matrix – exports from region r to s. B^{rr} is a matrix of domestic direct requirement coefficients between sectors in region r. The product equation $B^{rs}X^{s}$ represents intermediate use of exports; where B^{rs} is a matrix of direct requirement coefficients of exports from region r to s. Y^{rs} is exports for final consumption from region r to region s.

Equation (2) shows the equation in a given region r given m total regions.

$$\begin{pmatrix} X^1 \\ X^2 \\ X^3 \\ \vdots \\ X^m \end{pmatrix} = \begin{pmatrix} B^{11} & B^{12} & B^{13} & \dots & B^{1m} \\ B^{21} & B^{22} & B^{23} & \dots & B^{2m} \\ B^{31} & B^{32} & B^{33} & \dots & B^{3m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ B^{m1} & B^{m2} & B^{m3} & \dots & B^{mm} \end{pmatrix} \begin{pmatrix} X^1 \\ X^2 \\ X^3 \\ \vdots \\ X^m \end{pmatrix} + \begin{pmatrix} \sum_r Y^{1r} \\ \sum_r Y^{2r} \\ \sum_r Y^{3r} \\ \vdots \\ \sum_r Y^{mr} \end{pmatrix} \tag{2}$$

The footprint of a country r (ER^r) can be calculated by using Equation (3).

$$\begin{pmatrix} ER^{1r} \\ ER^{2r} \\ ER^{3r} \\ \vdots \\ ER^{mr} \end{pmatrix} = \begin{pmatrix} \hat{S}^1 & 0 & 0 & \dots & 0 \\ 0 & \hat{S}^2 & 0 & \dots & 0 \\ 0 & 0 & \hat{S}^3 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & \hat{S}^m \end{pmatrix} \left\{ \begin{pmatrix} I & 0 & 0 & \dots & 0 \\ 0 & I & 0 & \dots & 0 \\ 0 & 0 & I & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & I \end{pmatrix} - \begin{pmatrix} B^{11} & B^{12} & B^{13} & \dots & B^{1m} \\ B^{21} & B^{22} & B^{23} & \dots & B^{2m} \\ B^{31} & B^{32} & B^{33} & \dots & B^{3m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ B^{m1} & B^{m2} & B^{m3} & \dots & B^{mm} \end{pmatrix} \right\}^{-1} \begin{pmatrix} Y^{1r} \\ Y^{2r} \\ Y^{3r} \\ \vdots \\ Y^{mr} \end{pmatrix} \tag{3}$$

Where, ER^{mr} is a vector representing the footprint of consumption taking place in region r from resource extraction in region m. The sum of all elements in vectors ER^{1r} to ER^{mr} represents country r's footprint. $\hat{S}^m$ is a diagonal matrix containing domestic resource extraction coefficients for each industry in region m.

In order to simplify expression (3), we introduce expression (4):

$$\boldsymbol{X} = \hat{\boldsymbol{S}}\ (\mathbf{I}\text{-}\mathbf{A})^{-1}\ \hat{\boldsymbol{Y}} \tag{4}$$

where $\boldsymbol{X}$ is the matrix of a country's total footprint, $\hat{\boldsymbol{S}}$ presents the diagonal matrix of direct industry emissions or resource intensity, $\hat{\boldsymbol{Y}}$presents the diagonal matrix of final consumption. **U**= $(\mathbf{I}\text{-}\mathbf{A})^{-1}$ is the Leontief inverse, **D**=$\hat{\boldsymbol{S}}\ (\mathbf{I}\text{-}\mathbf{A})^{-1}$ is the matrix of total emissions or resource consumption factor**,** **W** =$\hat{\boldsymbol{V}}\ (\mathbf{I}\text{-}\mathbf{A})^{-1}$ is the matrix of total value-added factor. $\hat{\boldsymbol{V}}$ represents the diagonal matrix of industrial added value.

Assuming we have N countries in the world and M industrial sectors, to determine final export consumption influences on domestic emissions or resources consumed, we first introduce expression (5).

$$C_e^i = \sum_{j=1}^{N} \sum_{k=1}^{M} d_{ik} y_{kj} \tag{5}$$

Where, C_e^i is the total embodied emissions and resources consumed by a country i to satisfy the final consumption of all the other countries who imported from country *i*. d_{ik} is the total environmental emissions and resources consumption or emissions by country *i,* industry sector *k*. y_{kj} is the amount of consumption in country *j* from industry *k* (within country *i*).

The added value in country *i* induced by overseas final consumption (C_{ev}^i) is defined by expression (6):

$$C_{ev}^i = \sum_{j=1}^{N} \sum_{k=1}^{M} w_{ik} y_{kj} \tag{6}$$

Where w_{ik} is the added value by exports from country *i,* industry *k*. The emissions or resources consumptions per value-added unit (I_e) in country *i* induced by overseas total consumption is defined by expression (7).

$$I_e = C_e / C_{ev} \tag{7}$$

The total country *i* emissions or resources consumption from trade with all other countries is:

$$C_i = \sum_{j=1}^{N} \sum_{k=1}^{M} d_{jk} y_{ki} \tag{8}$$

The total country *i* value-added amount from international trade with all other countries is:

$$C_{iv} = \sum_{j=1}^{N} \sum_{k=1}^{N} w_{jk} y_{ki} \quad (9)$$

The international trade emissions or resources consumption per value-added unit from country *i* consumption is:

$$I_i = C_i / C_{iv} \quad (10)$$

In order to further explore the relationship between economic development, environmental emissions and resources consumption of a country's trade from a consumption-based perspective, we introduce the revised environmental emissions and resources usage terms of trade (ERTT) indicator. Our ERTT indicator is based on the sources of pollution from trade (PTT) indicator (Duan and Jiang, 2017; Grether and Mathys, 2013). PTT is the ratio of the average pollution content per USD of value-added in exports divided by the average pollution content per USD of value-added in imports (Duan and Jiang, 2017; Grether and Mathys, 2013).

If a country's ERTT is greater than 1 this country exports more environmental emission and resources consumption to its trade partners in order to gain 1 USD.

$$\text{ERTT} = I_e / I_i \quad (11)$$

3.2 Decoupling indicator

In order to identify the decoupling relationship between BRICS country economic development and environmental and resources consumption, we use a decoupling indicator based on Tapio (2005). In our study, the decoupling indicator (D_e) is:

$$D_e = \frac{\Delta ER_{t_n - t_0}\%}{\Delta G_{t_n - t_0}\%} \quad (12)$$

Where, ΔER% is the percentage change of each environmental emissions and resources usage consumption indicator from a starting year t_0 to final year t_n; ΔG% is the percentage change of GDP from a starting year t_0 to final year t_n.

In our study we evaluate D_e over six ranges, which are shown in Figure 1:

(1) If D_e >1.2; ΔER% >0; ΔG% >0, then the country shows expansive negative decoupling, meaning that economic growth is at the expense of increasing environmental emissions and resources consumption.
(2) If 0<D_e<1.2; ΔER% >0; ΔG% >0, then the country shows weak coupling, meaning that the speed of environmental emissions and resources consumption is slower than

economic growth.

(3) If D_e<0; ΔER% <0; ΔG% >0, then the country shows strong decoupling, meaning that although a country's economy is growing, its environmental emissions and resources consumption is decreasing.

(4) If D_e>1.2; ΔER% <0; ΔG% <0, then the country shows recessive decoupling, meaning that this country's economy is in recession; at the same time its environmental emissions and resources consumption is decreasing significantly.

(5) If 0< D_e <1.2; ΔER% <0; ΔG% <0, then the country shows weak negative decoupling, meaning that this country's economy is in recession, at the same time, its environmental emissions and resources consumption is decreasing slightly.

(6) If D_e<0; ΔER% >0; ΔG% <0, then the country shows strong negative decoupling, meaning that this country's economy is in recession, while its environmental emissions and resources consumption is still increasing.

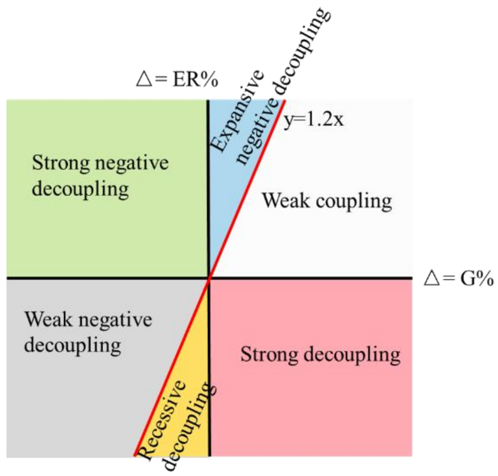

Figure 1 Various decoupling modes

3.3 Data sources

The MRIO input-output tables range from 1995 to 2015 and the industry sector intensity for environmental emissions (CO_2 and SO_2) and resources consumption (energy, land, water, and construction material) are from the Eora database. This database provides a time series of high-resolution IO tables with matching environmental and social satellite accounts for 190 countries; more features of this database can be found in https://www.worldmrio.com/. The environmental emissions (CO_2 and SO_2) of industrial activities in this database are based on the PRIMAPHIST dataset (https://www.pik-potsdam.de/members/johannes/primaphist-dataset-description). Energy consumption in our study includes natural gas, coal, petroleum, and electricity. The original data sources in this database were obtained from an IEA report. Land consumption mainly includes cropland and pasture land (http://www.earthstat.org/). Water consumption mainly includes grey, blue, and green water. The original data in this database were obtained from the Water Footprint Network. We only consider construction material consumption (Non-Metallic minerals) in this current work, the original data in this database were obtained from the EWMFA Database. Data on country GDP, final consumption and population were from the world bank database (https://data.worldbank.org/). All the economic data are consistent with US $ in 2010 prices. The income level country classification – *high, upper-middle, lower-middle and low* – is based on World Bank data https://datahelpdesk.worldbank.org/knowledgebase/articles/906519 .

4 Results

4.1 The trends of environmental and resources footprints of BRICS

Figure 1 shows BRICS country footprint trends as well as country related economic and social indicators from the years 1995 to 2015. The average annual growth rates of material, energy, land and water footprints in these countries over this period were 5.5%, 3.8%, 0.2%, and 9.8%, respectively. The average annual growth rates of environmental indicators of CO_2 footprint and SO_2 footprint were 4.8% and 2.2%, respectively, over this time period.

BRICS countries play an important role in overall global increasing of resources and environmental consumption. For instance, the consumptions of material, energy, land and water of BRICS countries accounted for 29.7%, 21.9%, 30.5% and 30.3% of total global consumption in 1995. These ratios became 49.6%, 34.7%, 32.0% and 9.8%, respectively in 2015. They accounted for 23.5% and 22.1% of global CO_2 and SO_2 emissions in 1995, and 39.0% and 33.8% in 2015, respectively.

Initially, at the individual country level, we evaluate the years 1995 and 2015 as an example. China is the only country with relatively stable increasing trends for the footprint indicators. Each of its indicator footprints is higher than the average global consumption level. This situation parallels its rapid domestic final consumption expenditure. According to World Bank statistics, China's expenditures increased by 4.5 times from 1995 to 2015, it is greatest increase from amongst the BRICS countries – Brazil increased by 71%, India increased by 2.2 times, Russia increased by 1.1 times and South Africa increased by 93%[3]. Given the high final consumption, China's increasing footprints trends include material increasing by 206%, energy by 172%, CO_2 by 248%, SO_2 by 89%, land by 25% and water by 676%, compared to other BRICS countries, China shows the largest increases in CO_2 and land footprints during this period. China's household final consumption – as an example – accounts for around 75% of final consumption during the period[4]. China's economic development enhanced residential income levels and living standards; thus, residential expenditure structure had significant changes from 1995 to 2015. In 1995, expenditures on food, cloth, household facilities, medical, transport, housing, and service accounted for 50%, 14%,

[3] https://data.worldbank.org/indicator/NE.CON.TOTL.KD?view=chart
[4] http://www.stats.gov.cn/tjsj/ndsj/

8%, 3%, 5%, 7% and 13%, respectively. However, in 2015, the above expenditures are 31%, 7%, 6%, 7%, 13%, 22% and 13%. This expenditure transition increased the demand of related commodities, which embodied high virtual CO_2 emissions and virtual land (Tian et al., 2019a; Tian et al., 2019b).

India had similar economic and income growth trends as China during this given period. India's final consumption increased by 2.2 times from 1995 to 2015. Compared to other indicators, India's material footprint – in our study it is construction material – showed the largest increase among BRICS countries of 219%. India's rapid urbanization, rising disposable incomes, and very large population base eager to improve lifestyle and quality, explain the material footprint increasing (IBEF, 2012). Unlike other indicators, India's land footprint shows a decreasing trend from 1995 to 2015. The reason for this decrease may be related to the increasing efficiency of land production intensity; its land consumption intensity for production decreased by 75% from 1995 to 2015.

Unlike China and India, final expenditure and income in Brazil are relatively unstable during this period; this economic instability also portends footprint instability. Brazil's material, energy, CO_2, SO_2, land and water footprints increased by 43%, 20%, 77%, 0.1%, 7.6% and 250%, respectively. There are two features of the increasing footprints in Brazil. First, the water footprint is the largest increasing indicator in Brazil from 1995 to 2015. The sectors that most contribute to the economy are also those most dependent on water, such as energy and agriculture[5]. Increasing population and middle-income groups, resulted in final consumption increases along with water consumption increases in Brazil (Salvo et al., 2015). The second feature is that along with China, Brazil is the only other country showing an increasing of land footprint from 1995 to 2015. This situation is likely due to changing food consumption structure caused by an increasing of middle-income level class (Salvo et al., 2015).

Compared to the above countries, Russia's and South Africa's footprints present different trends. In Russia, except water footprint, other footprints have lower growth. For land and SO_2 footprints, they show decreasing from 1995 to 2015. The decreasing situation may relate to decreasing population and unstable economic and social development in Russia (Wang and Jiang, 2019). The footprint growth trends in South Africa are lower than other countries, mainly due to its smaller size of economy. The fastest footprint growth is energy in South Africa, increasing by around 4.8 times from 1995 to 2015. This can be explained by the process of economic development in Africa, which shift from traditional agricultural-based economies to agricultural intensification, industrialization, value addition, expansion of the service sector and changes in consumption patterns (Odhiambo, 2012).

4.2 Economic development and environmental and resources footprints relationships

[5] https://www.worldbank.org/en/news/feature/2016/07/27/how-brazil-managing-water-resources-new-report-scd

Consumption-based decoupling performance can help identify the extent a country's economic development relies on global environmental resources consumption -- including domestic and trade consumption (Kan et al., 2019a). The BRICS country decoupling performance with selected indicators in the given period are summarized in Figure 3. Some highlights of the results are now presented.

Generally speaking, our results show that BRICS countries have varying decoupling trends across the different indicators. **For energy footprint**, China shows a stable weak coupling trend in the given time. Brazil, Russia and South Africa during 1995-2000 and 2010-2015 phases show strong negative decoupling. **For material footprint**, BRICS countries' weak coupling and decoupling are main feature in the given time. Country like Brazil (1995-2000) shows strong negative decoupling, such as with the decreasing 22% of GDP, its footprint increases by 12%. **For land footprint**, China is the only country maintaining a stable weak coupling trend over the study time period. Strong decoupling is shown as well, such as during the 2000-2005 phase in India, with the increasing 56% of GDP, its footprint decreases by 2%. From 2005-2010, India, Russia and South Africa show a strong decoupling trend. Strong negative decoupling occurred during 2010-2015 for Brazil and South Africa. **For water footprint**, most countries show expansive negative decoupling with their economic development during the 2010-2015 phase. Brazil, Russia and South Africa have strong negative decoupling. **In terms of CO_2 footprints**, the majority of BRICS countries have weak coupling, with Brazil (1995-2000 and 2010-2015) and Russia (2010-2015) showing strong negative decoupling. **For SO_2 footprint**, countries and phases for Brazil and South Africa (2005-2010), China (1995-2000), India (2010-2015) and Russia (2000-2005) each show strong decoupling.

In order to explain BRICS countries' decoupling relationship between economic and footprints, we take several examples to show the potential reasons combined with previous studies. **Weak coupling**—take CO_2 footprint which caused by energy consumption as example. For example, the weak coupling trend in India (2000-2005) is proper due to its low emission intensity. During this stage, the country is still mainly depended on service industry which has lower emission intensity than manufacturing industry (Wang et al., 2018). In China (1995-2010), the decrease of energy intensity and the cleaning of final energy consumption structure are the main facilitators to such a trend (Zhang and Da, 2015). **Strong coupling**-- China's SO_2 footprint during the 1995-2000 period is a strong coupling example. A potential explanation is China's national policy implementation. In the 9th and 10th national five-years plans environmental management played a large role during this period. The government highlighted reductions in SO_2 emissions due to acid rain events and broader international focus on this issue. In response to these concerns the government shutdown 84,000 enterprises with older technology, poor environmental pollution performance, and waste of resources. Economic incentives were also allocated for SO_2 emissions reduction. These incentives increased investment for environmental management technology. Also, permitting fees were installed for SO_2 emissions[6]. **Strong negative decoupling**-- Take Russia's energy footprint during the 1995-2000 phase as an example. Russia's economic development and exports have an excessive reliance on oil (Siddiqui, 2016). The international price of oil influences Russia's economic development. From 1995 to 2000, volatile oil prices with sudden rises and drops caused Russia's economic development to stagnate and even regress[7] (Mi and Liu, 2015). Brazil is also the country who is one of the largest suppliers of vital raw materials and primary commodity products (Siddiqui, 2016). Similar to Russia and oil price instability, the international price of primary commodities influence Brazil's economic development (Gereffi, 2015).

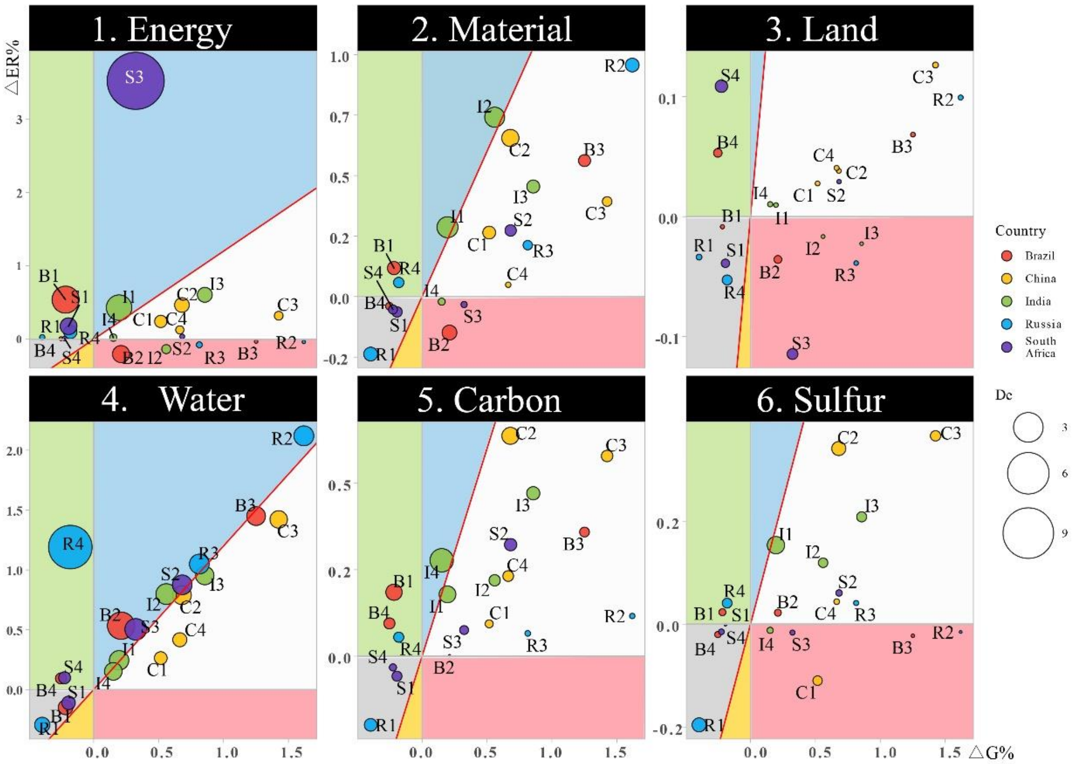

Figure 3 BRICS countries' decoupling performance from 1995 to 2015

Note: according to the description of the decoupling indicator (*De*) in section 3.2, the red line y=1.2x is the critical line. The background colors in this figure show the six *De* ranges. Green is strong negative decoupling, blue is expansive negative decoupling, white is weak coupling, pink is strong decoupling, yellow is recessive decoupling, grey is weak negative decoupling. B1, R1, I1, C1 and S1 are Brazil, Russia, India, China and South Africa in the 1995-2000 time period. B2, R2, I2, C2 and S2 are the BRICS countries in the 2000-2005 time period. B3, R3, I3, C3 and S3 are the BRICS countries in the 2005-2010 time period. B4, R4, I4, C4 and S4 are the BRICS countries in the 2010-2015 time period. The x-axes show GDP changes as ΔG%, the y-axes show footprint changes as ΔER%. The size of the circle shows the value of *De*.

6 http://www.gov.cn/zwgk/2006-06/05/content_300288.htm

7 http://intl.ce.cn/specials/zxxx/201307/31/t20130731_24622321.shtml

4.3 The imbalance in the relationship between economic development, and environmental emissions and resources usage of global trade

International trade plays a key role in embodied environmental and resources transfer. In order to obtain identical economic gains, the environmental emissions and resources consumption trends of BRICS country global trade is represented by ERTT ratios. If the ERTT country ratio is greater than 1, then in this country there is greater imbalance from exported embodied environmental resources and/or payments for imported economic USD value than are imported embodied environmental resources and/or USD value-added economic benefit from exports. Therefore, compared to the country's trade partner, on average, in order to obtain one USD economic benefit, this country paid more environmental emissions and resources consumption.

Table 1 shows the overall results. It is clear that Brazil's ERTT is about 0.8~0.9, except for the water footprint, indicating that Brazil gains environmental benefits from trade. The other BRICS countries have ERTTs greater than 1 -- except for water and land indicators. To complete a more nuanced investigation on the economic-environment imbalanced relationship, we divide the whole world into four groups according to country income level -- high, upper-middle, lower-middle and low[8]. The evolution of BRICS countries' ERTTs are shown in Table A3 in SI.

Generally speaking, for BRICS countries, the number trade partners with ERTT>1 and ERTT<1 varies for each indicator over the time period, trade partners with ERTT>1 are dominated by high-income countries. As an example, Brazil's CO_2 footprint in 1995 with ERTT>1 has a total of 53 countries, among these countries, 25 countries belong to high-income countries, accounting for 40% of total high-income countries in the world; which is the highest percentage from amongst all the income groups. Upper-middle-income and lower-middle-income groups represented the largest percentages within groups with ERTT<1.

To delve slightly deeper into the flow analysis, we arbitrarily select the top five countries in each income group on per capita level for a given year to further detail the relationship between economy, environmental emissions and resource usage, of trade with BRICS countries in 2015. This analysis will help identify some initial flow patterns for evaluation. These results are shown in Figure 4.

For energy traded, Germany is the top country gaining benefits from these BRICS countries. All BRICS countries gain more benefits from Ukraine and South Africa except South Africa. In these selected countries, South Africa has an ERTT > 1, indicating it is a net loser of energy in each case.

For material, Thailand is the top beneficiary with Brazil, China, Russia and South Africa; and Japan is the top beneficiary of trade with India. Turkey is the top loser to

[8] https://datahelpdesk.worldbank.org/knowledgebase/articles/906519

Brazil, China, India and Russia. Vietnam is the top loser to South Africa.

Among the selected countries, Japan and Malaysia are the top two countries obtaining virtual land benefits from BRICS countries. Argentina, Tajikistan and Zimbabwe are top three countries which lose most virtual land per USD traded to BRICS countries.

For virtual water, BRICS countries lose more virtual water to Japan and Germany in order to obtain 1 USD in economic benefits. Brazil, China and India gain most in virtual water in trade with Ethiopia. Russia and South Africa gain most virtual water in trade with Tajikistan.

For CO_2 emissions of traded, Germany is the biggest net beneficiary from trade with BRICS countries. For example, obtaining 1 USD benefit in German trade, Brazil, China, India, Russia and South Africa would export 1.33 times, 4.97 times, 5.06 times, 6.56 times and 4.31 times the CO_2 emission to Germany, respectively. Brazil and South Africa gain the largest CO_2 emissions benefits from Vietnam. China, India and Russia gain most CO_2 emissions benefits per USD traded from the Ukraine.

For SO_2, Germany and USA are the top two countries obtaining the most benefits from BRICS countries. The BRICS countries obtain most per unit benefits from Tajikistan and Zimbabwe.

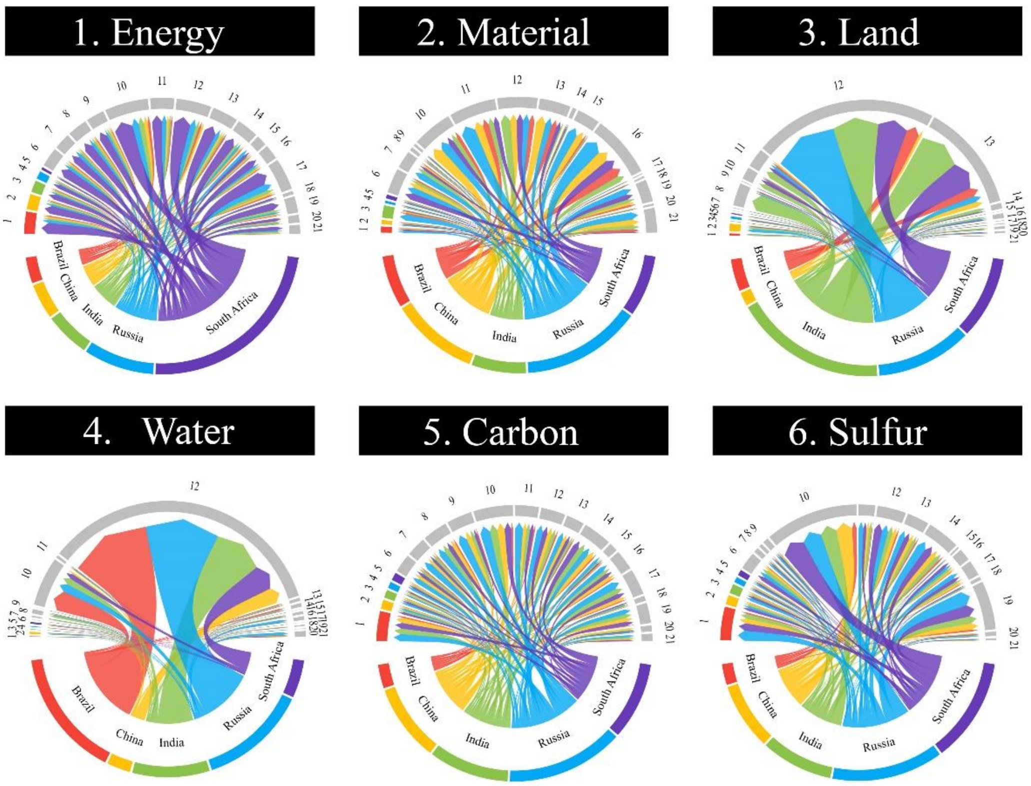

Figure 4 Imbalance between economic development, and environmental and resource usage of global trade with BRICS countries in 2015

Note: 1=Brazil, 2=China, 3=India, 4=Russia, 5=South Africa, 6=Argentina, 7=Australia, 8=Chile, 9=Ethiopia, 10=Germany, 11=Indonesia, 12=Japan, 13=Malaysia, 14=Mexico, 15=Tajikistan, 16=Thailand, 17=Turkey, 18=Ukraine, 19=USA, 20=Vietnam, 21=Zimbabwe. The figure drawing source in R software is from (Gu et al., 2014).

5 Discussions and Policy Implications

5.1 Overall Environmental Emission and Resource Consumption Implications

BRICS countries play a key role in global environmental emissions and resources usage during the period 1995 to 2015; especially for China and Brazil; the others will continue to emerge. Therefore, it is necessary to explore BRICS countries' footprint based full consumption perspective. Environmental and resources intensity and final consumption style play the key role in increasing countries' footprints (Hoekstra and Wiedmann, 2014). Compared to developed countries environmental and resources intensity for production, BRICS countries are still lower (Wu et al., 2018). In order to decrease their environmental and resources footprints a number of national policies become evident. First, production efficiency should be improved. These efficiencies may derive from investing in new manufacturing processes and technologies to minimize environmental damage and more efficient resource uses. To some extent policies that are voluntary such as subsidies for innovation can be adopted – examples include demonstration projects in China for circular economy and Brazil's regulations for waste minimization. In many situations there are significant mandatory regulatory policies in place for emissions; often these regulatory policies have been ignored from an enforcement perspective. This effort may be further supported by global supply chains requiring and acknowledging the need for enforcement of regulations. This issue relates to various importers and exporters in the global supply chain being aware of lax enforcement policies in BRICS countries and effectively implementing 'pollution haven' practices.

Global market participation is necessary for national economic development. BRICS countries – even with their large populations and emerging domestic economic systems – are not immune to this pressure. An export-oriented economy can drive an income effect in these countries that increases consumption (Andersson and Lindroth, 2001). Given this situation, rational and sustainable consumption should be further promoted in these countries. Policies should balance economic development and environment and resources; projects to encourage residential consumption behaviors, such as sharing economy principles, should be planned.

5.2 Coupling and Decoupling Discussion and Implications

BRICS country economies and social development are evolving. Governments and policymakers play core roles in managing the economy, environment and resources. For example, China's SO_2 footprint during the 1995-2000 period shows a strong coupling due to governmental incentives[9]. A general policy implication from this example observation is that the governmental role is critical for a sustainable relationship between economic and environmental emissions and resources usage management. Although China has a strong central government role, similar mechanisms have been used by developed countries effectively, and should be used by other BRICS countries. This effort should include national targets that are effectively included and national policies.

A country's strong negative decoupling trend represents a shift to excessive reliance on its primary commodity natural resource endowments. This would mean restructuring its industry and diversifying its industrial capabilities to reduce negative decoupling. For example, it is reasonable to invest in new product and markets by building educational and scientific capabilities, for which Russia is noted. Many of these issues seemed to be addressed in more recent time periods as both Russia and Brazil sought to diversify and extend their industrial capabilities; although some concerns with primary commodity agricultural aspects remain in both countries.

There may be other reasons for this strong negative decoupling; for which we only conjecture at this time. For example, lag effects from resources consumption during downturns, to keep factories operating for maintaining employment – companies keep producing even without market demand. Alternatively, industries may have maintained production to build inventories for future potential demands. These are only conjectures, but if these are causes of the negative decoupling situation countries and industries may realize that such efforts are counterproductive from a balance between economic development and environmental emissions and resources usage management.

None of the BRICS countries during this study period show any decoupling trends for water and CO_2 footprints. One potential explanation is the nexus relationship between footprint indicators, such as the energy-water nexus. It has been reported that total consumption of water for fossil fuel production is dominated by the large BRICS countries, such as Russia, China, Brazil, and India (Spang et al., 2014). Therefore, if energy consumption is increasing, then water consumption is also likely to increase. From this aspect the potential policy implication is that the environmental emissions and resources usage nexus should be investigated more carefully and highlighted as a national strategy for future environmental emissions and resources usage management.

Another potential explanation of water and CO_2 not showing any decoupling trends may be based on the historical developments of these environmental resources footprints that differentiates them from other ones; especially from strongly decoupled ones such as SO_2. Whereas, mitigation activities for resources or emissions may have occurred for health or severe resource scarcity, this severity – during this time period –

[9] http://www.gov.cn/zwgk/2006-06/05/content_300288.htm

was not observed in the BRICS countries. For example, the Kyoto protocol, which would have influenced CO_2 footprints, did not include most of the BRICS countries. There were no policy incentives for some of these countries. In Russia, which was a signatory, the lack of economic development allowed them to not worry about decoupling their CO_2 emissions from economic growth. The Kyoto protocol required countries to adopt practices to reduce CO_2 emissions to below 1990 levels. Russia had already met that goal due to poor economic performance. Additionally, it seems that water resources management policies to reduce or manage water usage efficiently were not policy instruments. Although India and South Africa have some water resources concerns, other BRICS countries did not during this time period. Industries may not view water scarcity a concern. But, as water scarcity becomes more common, especially in India, this lack of decoupling may be expected to decrease. Similarly, with the Paris accord and signatories receiving pressures to decrease CO_2 emissions, we may expect to see some future decoupling on CO_2 emissions.

5.3 Imbalance between Economy-Environment-Resources from Global Trade

The MRIO analysis provides insights into the broader global supply chain perspective; where trade may involve multiple steps across multiple countries. Generally speaking, in order to obtain identical economic gains, high-income countries gain relatively more environmental emissions and resources usage benefits from BRICS countries; that is, BRICS countries use more resources and generate greater emissions per USD gained from exports than when they deal with non-high-income countries. Alternatively, BRICS countries benefit from lower-middle-income and low-income countries. These observations are consistent with several previous studies which reveal the “imbalance exchange in trade” (Tian et al., 2018a; Wu et al., 2019b). This broader supply chain perspective is complex and makes it difficult to identify clear-cut potential explanations. There may be multiple reasons.

The imbalanced relationship between economic development and environmental emissions and resources usage from global trade across the supply chain can be related to country position in global value chains and country trade strategy. Take the specific case of Brazil and China trade as an example. What is particularly notable about Brazil’s trading relationship with China is that it is skewed to the export of products – both primary commodities and manufactured goods – with a very low level of processing and low value added. This situation is in contrast to Brazil’s imports from China whose imports tend to be technology intensive components and machinery with high value-added margins (Gereffi, 2015). The soybean value chain is a good example of a primary commodity trade item. About 95% of Brazil’s soybean exports to China in 2009 were unprocessed beans. In contrast, there were virtually no exports of soybean meal, flour, or oil to China; which are greater value-added goods. In order to pursue its strategy of promoting the Chinese soybean processing industry, China imposed a tariff of 9% on soybean oil imports, while the tariff on unprocessed soybean imports was only 3%. More processed imported soybean products also paid a higher value-added tax rate in China than unprocessed beans. Such a protectionist policy of tariff and non-tariff barriers increased the gains of China from Brazil in trade (Jenkins, 2012). A potential policy implication is for countries to improve their position in global value chain via technology innovation, building up the sustainable trade relationship between countries, and especially highlight the important role of environmental concerns and resources. These countries may not be in such positions initially, but as their economies mature, they should consider this important balance and the true value of their goods given the environmental emissions and resources usage degradation that arises from such international trade activities.

Many countries may not be aware of these deficits due to poor trade measures and metrics. The BRICS countries are between the more developed and less developed countries. Having ERTT-like indicators is necessary for governments to understand this global trade phenomenon that is hidden from policy makers who focus on simple measures such as overall import and export numbers. Environmental researchers have been cautioning about the use of pure economic measures. Policy makers and stakeholders need to raise awareness and programs to show that the benefits they are accruing from trade may be at a significant environmental cost.

BRICS countries can observe this issue from both directions and need to be cognizant of their own disparities with less developed countries. The policies they implement can help mitigate the issues with less developed countries. For example, Germany is a well-developed country, but may be getting the economic, environmental emissions and resources usage benefits, based on ERTT due to their efficient systems – they require fewer environmental emissions and resources consumption for greater economic returns from global trade. Building these efficiencies, and helping less developed country efficiencies may allow BRICS countries to build their relationships both with developed and developing countries. One such example – although the environmental results may still be uncertain – is China's belt and road initiative (Qian et al., 2019).

6 Conclusions

Rapid globalization has given developing countries, such as the BRICS countries, greater importance in global economic and environmental resources development. This study sought to evaluate various economic-environmental resources relationships within and between countries; especially the BRICS countries. The study used comprehensive MRIO data to investigate these issues from a consumption-based perspective for the period 1995 to 2015. This study conducted a comprehensive evaluation of six major environmental resources, including resource consumption and emissions indicators -- CO_2 emissions, SO_2 emissions, energy, land, water, and construction material resources.

Our main findings are the consumptions of material, energy, land and water of BRICS countries accounted for 29.7%, 21.9%, 30.5% and 30.3% of the whole world's consumption in 1995. These ratios changed to 49.6%, 34.7%, 32.0% and 9.8% accordingly in 2015. For CO_2 and SO_2 footprints, BRICS countries accounted for 23.5% and 22.1% of the whole world's emissions in 1995; 39.0% and 33.8% in 2015, respectively. Overall, most results show the BRICS countries' economic development were coupled with environmental emissions and resources consumption, especially in Brazil and Russia. In general, in order to obtain identical economic gains, BRICS countries are not overall beneficiaries in environmental and resources benefits from their global trade; especially when trading with high-income countries.

Limitation. The current study only revealed the economic, environmental emissions and resources usage relationship in BRICS countries at the macro level. This study did not disaggregate or downscale the analysis and issues to the industrial or product level. In addition, we did not fully examine the interactive relationships between the different footprint indicators. The policies that were recommended were based on conjectured reasoning. There are many additional results based on each of the sections and analyses completed in this paper that were not fully evaluated and require more evaluations. More nuanced policy and observational works and policies particular to internal BRICS countries and cross-cutting BRICS countries' issues need further investigations. These are important issues for future research.

Acknowledgment

This study is supported by the Natural Science Foundation of China (71704104, 71774100, 71690241, 71810107001, 71804071), Ministry of Science and Technology (SQ2019YFC190371/01), the Fundamental Research Funds for the China postdoctoral Science Foundation, the Shanghai Municipal Government (17XD1401800), the big data project funded by Shanghai Jiao Tong University (SJTU-2019UGBD-03), the Natural Science Foundation of Jiangsu Province (BK20180733), the Natural Science Research Project of Jiangsu Higher Education Institutions (18KJB610012). The authors are grateful for the comments from the anonymous reviewers of this paper.

Figure 2 Environmental and resource footprints of BRICS countries from 1995 to 2015

Table 1 BRICS Country Environmental Resources Terms of Trade (ERTT) for each indicator from 1995 to 2015

	1995		2000		2005		2010		2015	
	M	E	M	E	M	E	M	E	M	E
Brazil	0.98	0.97	1.17	0.99	1.19	1.02	1.06	0.96	1.10	0.98
China	1.24	1.07	1.17	1.03	1.21	1.05	1.19	1.06	1.13	1.02
India	1.25	1.08	1.37	1.04	1.18	1.03	1.04	1.05	1.06	1.06
Russia	5.32	1.20	5.53	1.31	3.60	1.20	3.82	1.16	3.64	1.12
South Africa	1.35	1.16	1.11	1.27	1.44	1.15	1.53	1.23	1.64	1.25
	S	L	S	L	S	L	S	L	S	L
Brazil	0.87	0.90	0.93	0.90	0.93	0.90	0.79	0.87	0.81	0.82
China	1.13	0.95	1.10	0.90	1.15	0.87	1.12	0.83	1.07	0.80
India	1.07	1.03	1.06	1.00	1.09	1.04	1.07	1.06	1.09	1.05
Russia	1.19	0.94	1.30	0.91	1.24	0.83	1.16	0.87	1.11	0.92
South Africa	1.19	0.91	1.23	0.92	1.16	0.90	1.19	1.02	1.24	0.93
	W	C	W	C	W	C	W	C	W	C
Brazil	1.06	0.89	1.06	0.94	1.11	0.96	1.07	0.86	1.06	0.90
China	0.84	1.13	0.95	1.12	0.96	1.16	0.97	1.15	0.86	1.10
India	0.99	1.08	1.05	1.09	1.06	1.09	1.06	1.08	0.99	1.12
Russia	0.99	1.33	0.95	1.48	0.98	1.37	0.98	1.29	0.71	1.25
South Africa	0.93	1.15	0.94	1.27	0.94	1.20	0.90	1.22	0.91	1.23

Note: M-material; E-energy; S-SO_2; L-land; W-water; C-CO_2

References

Anandarajah, G., Gambhir, A., 2014 India's CO_2 emission pathways to 2050: What role can renewables play? Applied Energy 131, 79-86.

Andersson, J.O., Lindroth, M., 2001. Ecologically unsustainable trade. Ecological Economics 37(1), 113-122.

Bagliani, M., Bravo, G., Dalmazzone, S., 2008. A consumption-based approach to environmental Kuznets curves using the ecological footprint indicator. Ecological Economics 65(3), 650-661.

Bond, P., 2015. BRICS and the sub-imperial location. BRICS: An anti-capitalist critique, 15-26.

Bruckner, M., Fischer, G., Tramberend, S., Giljum, S., 2015. Measuring telecouplings in the global land system: A review and comparative evaluation of land footprint accounting methods. Ecological Economics 114, 11-21.

Bruckner, M., Giljum, S., Lutz, C., Wiebe, K.S., 2012. Materials embodied in international trade-Global material extraction and consumption between 1995 and 2005. Global Environmental Change 22, 568-576.

Davis, S.J., Caldeira, K., 2010. Consumption-based accounting of CO_2 emissions. Proceedings of the National Academy of Sciences 107, 5687-5692.

Duan, Y., Jiang, X., 2017. Temporal change of China's pollution terms of trade and its determinants. Ecological Economics 132, 31-44.

Gereffi, G., 2015. Global value chains, development and emerging economies. Working paper series. United Nations University.

Grether, J.-M., Mathys, N.A., 2013. The pollution terms of trade and its five components. Journal of Development Economics 100, 19-31.

Gu, Z., Gu, L., Eils, R., Schlesner, M., Brors, B., 2014. Circlize implements and enhances circular visualization in R. Bioinformatics 30, 2811-2812.

Giljum, S., Lutter, S., Bruckner, M., Aparcana, S., 2013. A review and evaluation of available methods and data to calculate footprint-type (consumption-based) indicators for materials, water, land and carbon. Sustainable Europe Research Institute (SERI).

Hertwich, E.G., Peters, G.P., 2009. Carbon footprint of nations: a global, trade-linked analysis. Environmental Science & Technology 43, 6414-6420.

Hoekstra, A.Y., Wiedmann, T.O., 2014. Humanity's unsustainable environmental footprint. Science 344(6188), 1114-1117.

IBEF, 2012. Affordable housing in India: budding, expanding, compelling. India Brand Equity Foundation 1-20.

Jenkins, R., 2012. China and Brazil: Economic impacts of a growing relationship. Journal of Current Chinese Affairs 41, 21-47.

Jiang, J., Ye, B., Liu, J., 2019. Research on the peak of CO_2 emissions in the developing world: Current progress and future prospect. Applied Energy 235, 186-203.

Kan, S., Chen, B., Chen, G., 2019a. Worldwide energy use across global supply chains: Decoupled from economic growth? Applied Energy 250, 1235-1245.

Kan, S., Chen, B., Wu, X., Chen, Z., Chen, G., 2019b. Natural gas overview for world economy: From primary supply to final demand via global supply chains. Energy Policy 124, 215-225.

Kanemoto, K., Moran, D., Lenzen, M., Geschke, A., 2014. International trade undermines national emission reduction targets: New evidence from air pollution. Global Environmental Change 24, 52-59.

Lenzen, M., et al., 2012. International trade drives biodiversity threats in developing nations. Nature 486, 109-112.
Liu, X., Zhang, S., Bae, J., 2017a. The nexus of renewable energy-agriculture-environment in BRICS. Applied Energy 204, 489-496.
Liu, X., Klemes, J.J., Varbanov, P.S., Cucek, L., Qian, Y., 2017b. Virtual carbon and water flows embodied in international trade:a review on consumption-based analysis. Journal of Cleaner Production 146, 20-28.
Mi, J., Liu, Y.J., 2015. International oil price volatility and Russian economic growth. Eurasian economy (in Chinese) 5, 1-50.
Miglietta, P.P., Leo, F.D., Toma, P., 2017. Environmental Kuznets curve and the water footprint: anempirical analysis. Water and Environment Journal 31, 20-30.
Odhiambo, N.M., 2012. Economic growth and carbon emissions in South Africa: an empirical investigation. Journal of Applied Business Research 28(1), 37-46.
Perobelli, F.S., Faria, W.R., de Almeida Vale, V., 2015. The increase in Brazilian household income and its impact on CO_2 emissions: Evidence for 2003 and 2009 from input–output tables. Energy Economics 52, 228-239.
Pieterse, J.N., 2012. Global rebalancing: Crisis and the East-South turn, Globalization and Development in East Asia. Routledge, 48-72.
Qian, Y., Tian, X., Geng, Y., Zhong, S., Cui, X., Zhang, X., Moss, D.A., Bleischwitz, R., 2019. Driving factors of agricultural virtual water trade between China and the Belt and Road countries. Environmental Science & Technology 53, 5877-5886.
Salvo, G., Simas, M.S., Pacca, S.A., Guilhoto, J.J.M., Tomas, A.R.G., Abramovay, R., 2015. Estimating the human appropriation of land in Brazil by means of an Input-Output Economic Model and Ecological Footprint analysis. Ecological Indicators 53, 78-94.
Schandl, H., Hatfield-Dodds, S., Wiedmann, T., Geschke, A., Cai, Y.Y., West, J., Newth, D., Baynes, T., Lenzen, M., Owen, A., 2016. Decoupling global environmental pressure and economic growth: scenarios for energy use, materials use and carbon emissions. Journal of Cleaner Production 132, 45-56.
Siddiqui, K., 2016. Will the growth of the BRICs cause a shift in the global balance of economic power in the 21st century? International Journal of Political Economy 45, 315-338.
Spang, E., Moomaw, W., Gallagher, K., Kirshen, P., Marks, D., 2014. The water consumption of energy production: an international comparison. Environmental Research Letters 9, 105002.
Staritz, C., Reis, J.G., 2013. Global value chains, economic upgrading, and gender: Case studies of the horticulture, tourism, and call center industries. The World Bank.
Tapio, P., 2005. Towards a theory of decoupling: degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. Transport Policy 12, 137-151.
Tian, X., Bruckner, M., Geng, Y., Bleischwitz, R., 2019a. Trends and driving forces of China's virtual land consumption and trade. Land Use Policy 89, 104194.
Tian, X., Chen, B., Geng, Y., Zhong, S., Gao, C., Wilson, J., Cui, X., Dou, Y., 2019b. Energy footprint pathways of China. Energy 180, 330-340.
Tian, X., Geng, Y., Buonocore, E., Sarkis, J., Ulgiati, S., 2018a. Uncovering resource losses and gains in China's foreign trade. Journal of Cleaner Production 191, 78-86.
Tian, X., Geng, Y., Sarkis, J., Zhong, S., 2018b. Trends and features of embodied flows associated with international trade based on bibliometric analysis. Resources Conservation & Recycling 131, 148-157.
Tian, X., Sarkis, J., Geng, Y., Qian, Y., Gao, C., Bleischwitz, R., Xu, Y., 2018c. Evolution of China's

water footprint and virtual water trade: A global trade assessment. Environment International 121, 178-188.
Tukker, A., Bulavskaya, T., Giljum, S., Koning, A.D., Lutter, S., Simas, M., Stadler, K., Wood, R., 2016. Environmental and resource footprints in a global context: Europe's structural deficit in resource endowments. Global Environmental Change 40, 171-181.
Wang, Q., Jiang R., 2019. Is carbon emission growth decoupled from economic growth in emerging countries? New insights from labor and investment effects. Journal of Cleaner Production 119188.
Wang, Q., Song, X., 2019. Evolution and drivers India's coal footprint with virtual coal flows in the globalized world. Journal of Cleaner Production 230, 286-301.
Wang, R., Hertwich, E., Zimmerman, J.B., 2016. Virtual water flows uphill toward money. Environmental Science & Technology 50, 12320-12330.
Wang, Z.Y., Meng, J., Zheng, H.R., Shao, S., Wang, D.P., Mi, Z.F., Guan, D.B., 2018. Temporal change in India's imbalance of carbon emissions embodied in international trade. Applied Energy 231, 914-925.
Wiedmann, T.O., Schandl, H., Moran, D., 2015. The footprint of using metals: new metrics of consumption and productivity. Environmental Economics and Policy Studies 17(3), 369-388.
Weinzettel, J., Hertwich, E.G., Peters, G.P., Steen-Olsen, K., Galli, A., 2013. Affluence drives the global displacement of land use. Global Environmental Change 23, 433-438.
Wu, R., Geng, Y., Liu, W., 2017. Trends of natural resource footprints in the BRIC (Brazil, Russia, India and China) countries. Journal of Cleaner Production 142, 775-782.
Wu, S., Lei, Y., Li, S., 2019a. CO_2 emissions from household consumption at the provincial level and interprovincial transfer in China. Journal of Cleaner Production 210, 93-104.
Wu, X., Guo, J., Li, C., Shao, L., Han, M., Chen, G., 2019b. Global socio-hydrology: An overview of virtual water use by the world economy from source of exploitation to sink of final consumption. Journal of Hydrology 573, 794-810.
Wu, Y., Zhu, Q., Zhu, B., 2018. Comparisons of decoupling trends of global economic growth and energy consumption between developed and developing countries. Energy Policy 116, 30-38.
Yang, X., Lou, F., Sun, M., Wang, R., Wang, Y., 2017. Study of the relationship between greenhouse gas emissions and the economic growth of Russia based on the Environmental Kuznets Curve. Applied Energy 193, 162-173.
Yu, Y., Feng, K., Hubacek, K., 2014. China's unequal ecological exchange. Ecological Indicators 47, 156-163.
Zhang, M., Bai, C., Zhou, M., 2018. Decomposition analysis for assessing the progress in decoupling relationship between coal consumption and economic growth in China. Resources, Conservation and Recycling 129, 454-462.
Zhang, Y.J., Da, Y.B., 2015. The decomposition of energy-related carbon emission and its decoupling with economic growth in China. Renewable and Sustainable Energy Reviews 41, 1255-1266.
Zhang, W., Wang, F., Hubacek, K., Liu, Y., Wang, J., Feng, K., Jiang, L., Jiang, H., Zhang, B., Bi, J., 2018. Unequal exchange of air pollution and economic benefits embodied in China's exports. Environmental Science & Technology 52, 3888-3898.
Zhao, X., Liao, X., Chen, B., Tillotson, M.R., Guo, W., Li, Y., 2019. Accounting global grey water footprint from both consumption and production perspectives. Journal of Cleaner Production 225, 963-971.
Zheng, X., Wang, R., Wood, R., Wang, C., Hertwich, E.G., 2018. High sensitivity of metal footprint to national GDP in part explained by capital formation. Nature Geoscience 11, 269-273.