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A quantitative model for environmentally sustainable supply chain performance measurement

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ABSTRACT

The development of robust mechanisms for supply chain performance measurement have been identified as an integral step needed for the transition towards sustainable supply chain systems and a greener global economy. However, measuring the environmental performance of supply chains is a challenging task, due to several factors, such as the lack of standardised methodologies and the inherent multi-criteria nature of the problem. By leveraging the capability of a Multi-Regional Input–Output framework to handle the complex and global nature of supply chains, the current work presents a robust environmental sustainable performance measurement model underpinned by *industrial lifecycle thinking*.

As a result, some theoretical insights are provided and an empirical application of the model to the Metal Products industry of the BRICS (Brazil, Russia, India, China, and South Africa) nations undertaken in an attempt to address some of the methodological and applied measurement challenges. In particular, this allowed the modelling of carbon emissions trends within, and between the BRICS nations and with the Rest-of-the-World over a 20-year period (1992–2011) as well as providing an opportunity to hypothesis on their future carbon emissions performances. Specific analyses of the Metal Product industry showed that demand represents the main driver for the increasing carbon footprint. However, the overall decline in reported carbon footprint was due to improvements in emissions intensity and efficiency gains induced by technology. The study further assesses the effects of imports and economic growth on carbon footprint and discusses the implications of the study to sustainability transition processes in the BRICS nations.

1. Introduction

The transition towards sustainable supply chains (Ding, Liu, & Zheng, 2016) has encouraged businesses to align their operations to practices that are judged to be environmentally sustainable (Dey, Laguardia, & Srinivasan, 2011; Hassini, Surti, & Searcy, 2012, Jaehn, 2016). The development of models and their application to production and supply networks in order to measure environmental performance has therefore been identified as a key element towards such transition. Environmental performance measurement as used in this paper draws on the concept of the natural resource based-view proposed by Hart (1995); a concept that examines the use of natural resources and their resultant impact.

Taticchi, Garengo, Nudurupati, Tonelli, and Pasqualino (2015) and Ahi and Searcy (2015), have reported on the importance of performance measurement for supply chain sustainability given the opportunities for continuous improvement (Zhu, 2014). Despite the reported importance, measuring the environmental performance of supply chains has become a challenge as reiterated by Lehtinen and Ahola (2010) and Hassini et al. (2012), who reported that incompatibilities exist between the known principles of performance measures and supply chains. The performance measurement literature appears to be biased towards intra-organisational measures of performance (Lehtinen & Ahola, 2010) as opposed to the extended, complex and dynamic network nature, which characterises supply chains (Gunasekaran, Patel, &

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McGaughey, 2004; Varsei, Soosay, Fahimnia, & Sarkis, 2014). All these issues imply that performance measurement models for sustainable supply chains focus only on direct impacts, and thus do not take a holistic view of the supply chain. Other issues that pose challenges for building reliable sustainable supply chain performance measurement approaches include, the multiple measures that must be employed to characterise the performance driven by data (Afful-Dadzie, Afful-Dadzie, & Turkson, 2016) and the focus on reporting green supply chain management initiatives implementation rather than outcomes (Zhu, Sarkis, & Lai, 2008). It has also been reported that performance measures are multi-faceted (Genovese, Morris, Piccolo, & Koh, 2017) and are characterised by inconsistent methodologies as expounded by Font and Harris (2004).

In order to address some of the highlighted issues, this paper leverages on the extended capability and visibility of the Multi-Regional Input-Output (MRIO) framework (Miller & Blair, 2009) in handling the complex and global nature of supply chains operations to present a robust environmental sustainable performance measurement model underpinned by *industrial lifecycle thinking*. This analytical viewpoint provides a holistic view and visibility of the global economy such that supply chain dependences and interactions are captured and assessed in a consistent framework. An industry-level perspective of the global supply chain is adopted for this study because, most value-added activities of the supply chain take place at the industry level compared to the process, product or firm level of the supply chain (Gereffi, Humphrey, & Sturgeon, 2005). The mathematical basis of the model is derived based on the MRIO framework (Miller & Blair, 2009) for supply chain carbon emissions quantification and analyses. Gonzalez et al. (2015) have reiterated how mathematical models and solution methods can provide quantifiable information and structured opportunities to evaluate, propose, test and implement action for the transition towards environmental sustainability.

To provide a context for the application of the environmental sustainability measurement model, an assessment is carried out over a 20-year period (1992–2011) in the BRICS nations (namely: Brazil, Russia, India, China and South Africa) with a focus on the Metal Industry in these countries. Attention is focused on the BRICS nations because, in the last decade, there have been growing international concerns on the environmental damage associated with the accelerated economic growth of these countries. These concerns have been reported in the scholarly literature (Lai & Wong, 2012; Wu, Liu, Liu, Fang, & Xu, 2015) as well as in the mainstream media platforms (Guardian, 2011; Washington Post, 2014). Insights into the low-carbon management of the supply chains of these nations have therefore become an issue of high importance in the current climate of sustainability awareness and international climate change debates. The Metal Industry was chosen, as it is a major heavy industrial sector, which received special attention for decarbonisation efforts in the recently published Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC, 2014).

In this paper, the carbon emissions assessment process in the selected industrial supply chains is carried out from a consumption-based perspective (Takahashi et al., 2014) between 1992 and 2011. This enables supply chain carbon emissions intensities (presented as a measure of the overall efficiencies of the considered industrial systems) of the BRICS nations to be assessed, thus providing a standardised way for similarly structured industries within these countries to be compared over time horizons. The time series analysis of carbon emissions intensities profiles provides the right context to discuss recent trends in economic growth in the BRICS countries and the environmental consequences of such growth. Additionally, based on the demand for final goods and services, this paper also presents and assesses the carbon emissions footprint in absolute terms, making provision for carbon emissions embodied in imported and exported goods and services.

In the light of the context presented above, the contributions of this paper can be summarised as follows:

- An *industrial lifecycle thinking* concept is introduced as a way of analysing environmental sustainability impacts through the general input-output methodological framework.
- Based on a 20-year time series analysis, the future industrial environmental sustainability performance outlooks of BRICS countries are hypothesised.
- Industry-level Supply Chain Efficiencies and Footprint accounts as well as targeted measurements of a specific industrial sector are generated, allowing for cross-country analyses in a consistent manner.
- The influences of indirect supply chain emissions on environmental sustainability performance are assessed.
- The development of a 20-year environmental performance model for any targeted industry in any country is exemplified, along with contextual assessment, discussions and implications of the findings.

To address fully the issues highlighted in this work, the remainder of the paper is organised as follows: In Section 2, a literature review is conducted on approaches for supply chains environmental impact assessment. The review provides the context and lays the foundation for the developments and contributions made in this paper. Details of the general methodological notes and theoretical formulations are provided in Section 3. In Section 4, key findings and results are analysed and discussed, highlighting the implications of the research to supply chain management. Some concluding remarks are drawn in Section 5.

2. Literature review

2.1. Industry-level carbon emissions measurement

The contemporary view of supply chain emphasises a network of multiple relationships where value can be added (Horvath, 2001). Such relationships can be between products (Ganesh, Raghunathan, & Rajendran, 2014) or even processes, firms and industries as elaborated by Lambert and Cooper (2000). Gereffi et al. (2005), however report on how the most value added activities within the global supply chain network occurs at the industry level. Azapagic et al. (2000) have also pointed out that industrial systems are an integral part of the economy since they determine the flows of materials and energy, rendering them a source of environmental degradation and resource depletion. Industrial supply chains, therefore, play a central role in identifying and implementing more environmentally sustainable options. To this end, this study adopts an industrial-level perspective to the supply chain environmental performance measurement (Refer to Fig. 1).

This viewpoint is taken because the industrial supply chains and systems are what binds nations together within the global economy and so it provides assistance in gaining an understanding of the interrelationship within cross-country supply chains. This is in line with the recommendation by Sundarakani, De Souza, Goh, Wagner, and Manikandan (2010) who stated that there is the need to study carbon footprint measurement across supply chains as a way to better understand the environmental impact in global production networks.

Frameworks such as Material Flow Analyses (MuÏler, Hilty, Widmer, Schluep, & Faulstich, 2014), Product Life Cycle Accounting (Koh et al, 2013) and Corporate Value Chain Accounting have been employed respectively at the material, product and firm -levels of

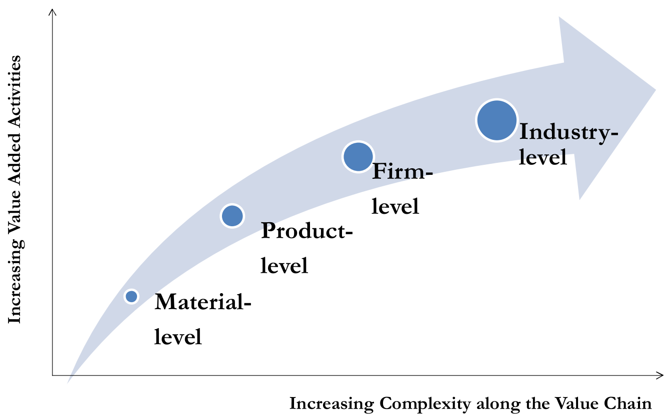


Fig. 1. A hierarchal perspective of the value chain and complexity of supply chain systems.

the value chain as highlighted in Fig. 1. It should be noted that Life Cycle Assessment (LCA) has been used as one of the main general constructs for environmental performance measurements (Acquaye, Genovese, Barrett, & Koh, 2014; Ibn-Mohammed et al., 2017). Ongoing work by the Life Cycle Impact Assessment workgroup of the United Nations Environmental Programme Life Cycle Initiative (Guinée, 2002) seeks to provide harmonisation and guidance in LCA studies. This LCA framework based on the ISO14000 series has been developed for product supply chains as reported by UNEP and SETAC (2011). As such, for industry-level supply chain analysis (which is higher up the value chain) the specifics of the LCA framework (International Standard Organisation, 1998) are not applicable.

The current research, therefore, argues for what it describes as *industrial lifecycle thinking,* which can be assumed as taking a similar logic of lifecycle thinking (Hu & Bidanda, 2009; Yang & Song, 2006) applicable to product supply chains. The *industrial lifecycle thinking* is presented as taking a holistic view of the global industrial supply chain in which the complex industry-level supply chain dependences and interactions (upstream) and their resultant impact as a result of demand (downstream) are recognised, thus allowing for strategies and policies to be developed and implemented.

Such *industrial lifecycle thinking* suggests that the interaction between industrial supply chains and the natural environment are characterised by the following:

i. Industrial supply chains are at the highest level of the supply chain hierarchy and are therefore characterised by higher complexity and value-added activities (Timmer, Erumban, Los, Stehrer, & de Vries, 2014).
ii. The economies of different countries are connected and characterised by industrial supply chains (Neilson, Pritchard, & Yeung, 2014). Accordingly, linkages and dependencies between economies of different nations can also be viewed from an industrial-level perspective.
iii. For an industry to produce an output, resources are required from the same industry and from other industries, both within its country of origin and internationally. (Miller & Blair, 2009).
iv. Any final product or service produced by any industry is the result of many other products or services used as inputs at different supply chain tiers (Acquaye et al., 2017).
v. Products and services that are produced by any industry can be used by the same industry, by other industries or as part of the final demand category consisting of households, government purchases, exports, stocks (Kucukvar, Egilmez, & Tatari, 2014).
vi. The assessment of dependences and impacts of industrial supply chains must inform the management of these impacts (Marchi, Maria, & Micelli, 2013).

To gain an understanding of the assessments of carbon footprints, appropriate frameworks and methodologies must be used. The Intergovernmental Panel on Climate Change (2001) recommended two basic modelling approaches used to examine the linkages between a supply chain and the environment. These are the bottom-up (based on process modelling) and the top-down (based on macro-economic modelling) approaches.

Although the bottom-up process approach is based on LCA principles (Majeau-Bettez, Strømman, & Hertwich, 2011) and is consistent with the logic of lifecycle thinking (Hu & Bidanda, 2009), the IPCC (2001) explains that in the top-down modelling approach, economic theory and techniques are applied to historical data on consumption and prices in order to model the final demand for goods and services and their resultant environmental impacts. To this end, we adopt a top-down modelling approach in this study since it addresses system complexity issues (Ewing et al., 2012) and system boundary completeness limitations (Ward et al., 2017) by providing a holistic perspective (Abbasi & Nilsson, 2012) whilst addressing the aforementioned key challenges related to *industrial lifecycle thinking.*

2.2. Industry-level carbon emissions management

In addition to pressure from three main stakeholder groups (civic society including consumers, media and regulatory bodies), the theory of Business Case for Sustainability (Schaltegger, Lüdeke-Freund, & Hansen, 2012) also explains why business now see the measurement and management of their supply chain impact as an important aspect of their operations. Such a theory emphasises how the links between voluntary environmental and economic success can be managed, advanced, or innovated.

While low-carbon supply chain management may initially begin with carbon emissions assessment, in terms of *industrial lifecycle thinking,* how this informs the management of the impacts must also be taken into account. In fact, it should be a continuous learning in which carbon footprint assessment feeds into low-carbon management and vice versa. It has been reported that no single policy can be used to adequately manage the impacts of carbon emissions on the environment (Heltberg, Siegel, & Jorgensen, 2009) and that decarbonisation efforts should consist of a portfolio of policies (Fischer & Newell, 2008).

Managing carbon emissions at the industry-level must therefore take into account these principles. In fact, in an attempt to identify different drivers of global industry-related greenhouse gas (GHG) emissions, the Intergovernmental panel on Climate Change in its 5th Assessment Report, decomposed GHGs using a *kaya-like* identity (Fischedick et al., 2014). This was expressed as:

$$G = \frac{G}{E} \times \frac{E}{M} \times \frac{M}{P} \times \frac{P}{S} \times S,$$

where:

G GHG emissions of the industrial sector within a specific time frame.
E Industrial sector energy consumption.
M Total global production of materials in that period.
P Stock of products created from these materials.
S Total demand for products and services.

Since this *kaya-like* identity captures the drivers of emissions in industry, it can also be used to identify key mitigation opportunities available within industrial sectors.

$\frac{G}{E}$ represents the emissions intensity of the industrial sector expressed as a ratio to the energy used. Emissions efficiency therefore means a reduction in the value of G/E.

$\frac{E}{M}$ measures the energy intensity of energy input to industrial output (Arens, Worrell, & Schleich, 2012, Freeman, Niefer, & Roop, 1997); that is the energy used to create materials from ores, oil and biomass, etc. The aim of energy intensity supply chain strategies or policies is to reduce E/M.

$\frac{M}{P}$ identifies material intensity, namely a measure of the amount of material needed to create a product and maintain the stock of product (Allwood, Ashby, Gutowski, & Worrell, 2011). Material efficiency therefore means providing material services with less material production and processing.

$\frac{P}{S}$ provides a measure on the intensity of use or the level of service provided by a product (Roy, 2000). A reduction in P/S refers to a reduction in product-service intensity

S represents total demand for products and services and it is a function of variables such as population, wealth, lifestyle and the whole social system of expectation and aspiration (Alcott, 2012; Hubacek, Feng, & Chen, 2011). A reduction in total demand will lead to a decrease in industrial emissions.

Following the outline of these mechanisms by which industrial-level emissions can be addressed, supply chain emissions assessment must capture some of these drivers in such a way that there is a continuous learning and improvement process in which carbon footprint assessment feeds into low-carbon management and vice versa.

This study, therefore, argues that in order to implement *industrial lifecycle thinking* approaches, the developments made in carbon footprint assessment using top-down models consisting of macro-economic techniques (as discussed in Section 2.1) should be used to inform industry-level carbon emissions management (as highlighted in Section 2.2).

3. Methodological development

3.1. General framework

As outlined in the Section 2, the research methodology must encapsulate a framework that is able to capture the complexities of the production and consumption activities of industrial supply chains and related impacts on the environment. As such, from an economic perspective, the general Input–Output (IO) approach originally developed by Leontief (1936) is employed as the methodological basis, given its ability to reproduce production and consumption processes within an economy (Prell, Feng, Sun, Geores, & Hubacek, 2014). Input–Output models record monetary transactions representing flows of resources (products and services) from each industrial sector considered as a producer to each of the other sectors (expressing final demands) considered as consumers (Court, Munday, Roberts, & Turner, 2015). This general model can thus be transformed into a physical one by integrating it with environmental factors (in this case carbon emissions, that can be considered as a good proxy for a wide range of other indicators; see Genovese et al., 2017). The complex flow of resources in the supply chain network which is captured within the input-output framework has been described by Wu and Zang (2005) as depicting both a pull (related to the intermediate inputs from different sectors into a given sector) and push (related to the intermediate use in a given sector) effects.

The model used to assess the relationships and dependences within and among the industrial supply chains of the BRICS nations and with the Rest of the World (ROW) can be represented as shown in Fig. 2, where each block represents the supply from

	Brazil (B)	Russia (R)	India (I)	China (C)	South Africa (SA)	ROW
Brazil (B)	B→B	B→R	B→I	B→C	B→SA	B→ROW
Russia (R)	R→B	R→R	R→I	R→C	R→SA	R→ROW
India (I)	I→B	I→R	I→I	I→C	I→SA	I→ROW
China (C)	C→B	C→R	C→I	C→C	C→SA	C→ROW
South Africa (SA)	SA→B	SA→R	SA→I	SA→C	SA→SA	SA→ROW
Rest-of-the-World (ROW)	ROW→B	ROW →R	ROW →I	ROW →C	ROW →SA	ROW →ROW

Fig. 2. Model used to capture dependences within and among the BRICS nations and the ROW.

the industries in the *row* nation to the use by the industries in the *column* nation.

Following this model, if it is assumed that all outputs of an industrial sector are produced with the same physical flow intensity (Miller & Blair, 2009), then the general input-output methodology and assumptions can be applied (Chakraborty & Mukhopadhyay, 2014).

For any economy, it can be shown that:

$$x_i = x_j = \sum_j z_{ij} + \sum_i y_i, \tag{1}$$

where:

$x_i = x_j$ The total sector products consumed (row total), x_i or the total industry production output (column total) x_j. Theoretically, given that the IO table is balanced, $x_i = x_j$ and the units are expressed in million $

$[z_{ij}]$ The matrix representation of the intermediate consumption; that is, the amount of product (i) used as an intermediate input in the production process of industry (j). The matrix representation is given in monetary terms (million $)

y_i The final demand of products i which represents the request (by households, public sector, capital goods, exports, etc.) for products i

In a generalised form, Eq. (1) can be expressed as:

$$\boldsymbol{x} = \boldsymbol{Z} + \boldsymbol{y} \tag{2}$$

For any economy, it can also be shown that:

$$\boldsymbol{A} = [a_{ij}] = \frac{[z_{ij}]}{x_j} \tag{3}$$

Where:

A Represents the technical coefficient matrix of the whole economy, as it defines the technology of all the individual industries. It is a unit-less matrix.

a_{ij} Represent all the elements of the technical coefficient matrix, A. The technical coefficient matrix consists of the technology matrix for each of the industries in the economy. Hence for an industry where $j = k$, its technology matrix is given by elements of the matrix $[a_{ik}]$. These elements are all the products and services (example: raw materials, machinery, energy, goods, transport, services, etc) required from its own and all other industries in the economy which enables that industry to produce a unit of output.

Hence from Eq. (3):

$[z_{ij}] = \boldsymbol{A}\cdot[\widehat{x_j}]$, where $[\widehat{x_j}]$ is the diagonalised $[x_j]$. In a generalised form: $\boldsymbol{Z} = \boldsymbol{A}\cdot\boldsymbol{x}$.

Therefore from Eq. (2) where: $\boldsymbol{x} = \boldsymbol{Z} + \boldsymbol{y}$, it follows that: $\boldsymbol{x} = \boldsymbol{A}\cdot\boldsymbol{x} + \boldsymbol{y}$. Solving for x and expressing in matrix notations:

$$\underline{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\cdot\underline{y} \tag{4}$$

$\boldsymbol{I}$ is the identity matrix and $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ known as the Leontief inverse matrix, $\boldsymbol{L}$ (Ebiefung & Kostreva, 1993).

The implication on the expansion of the Leontief Inverse Matrix $\boldsymbol{L}$ is that, the complete supply chain requirement at any tier n can be evaluated given that:

$$\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1} = A^0 + A^1 + A^2 + A^3 + \ldots A^n \tag{5}$$

$$\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1}$$

Therefore describes the total (direct and indirect) requirements that are needed at all tiers $(0,\ 1,\ 2,\ 3,\ \ldots,\ldots.n)$ of the industrial supply chain by an industry to produce a unit of output. As presented, the Leontief Inverse Matrix is in a generic format and so it can be specified to any number of regions/countries within a multi-regional system.

Acquaye et al. (2014) explain that capturing the direct and indirect requirements at all tiers ensures a complete supply chain visibility, a key requirement in environmental modelling across supply chains (Sundarakani et al., 2010). Bazan, Jaber, and Zanoni (2015) and Acquaye et al. (2017), have also emphasised that assessment models for supply chains need to account for a more comprehensive picture that accurately evaluates the true cost of capturing carbon emissions and allows for a more responsible approach to supply chain policies and decision-making practices.

The Leontief Inverse Matrix expression presented in Eq. (5) does not encapsulate the multi-country nature that the framework in Fig. 2 seeks to uphold. In addition, it has not yet been integrated with environmental factors for the transformation of the economic model into a physical one. Therefore, the following sub-section addresses these developments.

3.2. Multi-regional supply chain dependencies of the BRICS nations

Following on from Eq. (4), a Multi-Regional Input–Output (MRIO) model of the BRICS nations can be defined as a framework that is able to capture the inter-relationship and represent the dependences of the nations and the ROW in a single system as highlighted by the model in Fig. 2.

The technical coefficient matrix (see Eq. (3) of the BRICS and ROW framework can thus be presented below:

$$A = \left(I - \begin{bmatrix} A_{B,B} & A_{B,R} & A_{B,I} & A_{B,C} & A_{B,SA} & A_{B,ROW} \\ A_{R,B} & A_{R,R} & A_{R,I} & A_{R,C} & A_{R,SA} & A_{R,ROW} \\ A_{I,B} & A_{I,R} & A_{I,I} & A_{I,C} & A_{I,SA} & A_{I,ROW} \\ A_{C,B} & A_{C,R} & A_{C,I} & A_{C,C} & A_{C,SA} & A_{C,ROW} \\ A_{SA,B} & A_{SA,R} & A_{SA,I} & A_{SA,C} & A_{SA,SA} & A_{SA,ROW} \\ A_{ROW,B} & A_{ROW,R} & A_{ROW,I} & A_{ROW,C} & A_{ROW,SA} & A_{ROW,ROW} \end{bmatrix} \right) \tag{6}$$

Combining the BRICS nations with the ROW as presented in Eq. (6) achieves two objectives. First, it improves the focus on the BRICS nations within a global supply chain network thus ensuring that the dependencies among these nations are assessed with more details. Secondly, the BRICS nations are not closed economies to all other countries in the world. Hence, the model takes into account the fact that there are also resource flows (products and services) between all other countries from the ROW region and the BRICS nations.

From Eq. (5), the Leontief Inverse matrix can be structured as:

$$L = \left(I - \begin{bmatrix} A_{B,B} & A_{B,R} & A_{B,I} & A_{B,C} & A_{B,SA} & A_{B,ROW} \\ A_{R,B} & A_{R,R} & A_{R,I} & A_{R,C} & A_{R,SA} & A_{R,ROW} \\ A_{I,B} & A_{I,R} & A_{I,I} & A_{I,C} & A_{I,SA} & A_{I,ROW} \\ A_{C,B} & A_{C,R} & A_{C,I} & A_{C,C} & A_{C,SA} & A_{C,ROW} \\ A_{SA,B} & A_{SA,R} & A_{SA,I} & A_{SA,C} & A_{SA,SA} & A_{SA,ROW} \\ A_{ROW,B} & A_{ROW,R} & A_{ROW,I} & A_{ROW,C} & A_{ROW,SA} & A_{ROW,ROW} \end{bmatrix} \right) \tag{7}$$

3.3. MRIO-based carbon emissions assessments of the industrial supply chain

The study evaluates the carbon emissions of the BRICS nations in terms of their intensities (used as a measure of the efficiencies of the industrial supply chains) and footprints as a result of the final demand for goods and services. The following sub-sections present the developments made in these respect.

3.3.1. Industrial carbon emissions intensities

As previously explained in Section 3.1, the input–output model (as in the Leontief framework in Eq. (7) is transformed into a physical one by integrating it with environmental factors (in this case carbon).

Let:

E_j Represent the direct carbon emissions output [1000 tons $CO_{2\text{-eq}}$] for any industry j in a BRICS nation or ROW region.

Given that x_j is the total industry production output expressed in million $, the direct intensity matrix for carbon of any industry j is given by:

$$e_d = \frac{E_j}{x_j} \tag{8}$$

This provides a measure of the direct carbon emissions intensity per unit dollar of an industry. This is a limited measure and does not account for any upstream activities of the industrial supply chain. This is because e_d only measures the efficiency of an industry from a production-based perspective (Jakob, Steckel, & Edenhofer, 2014), meaning that only the direct emissions that occur within the fixed boundary of a country's industrial activities are assessed.

e_d values from all the industries can be combined in a row matrix $\underline{e_d}$. Based on Eq. (5), given that the Leontief Inverse Matrix represents the total (that is, direct and indirect) activities of the industrial supply chain, the Total Intensity Matrix in terms of carbon emissions intensities is therefore expressed as:

$$\begin{aligned} \text{Total Intensity} &= \underline{e_d}\cdot\boldsymbol{L} = \underline{e_d}\cdot(\boldsymbol{I} - \boldsymbol{A})^{-1} \\ &= \underline{e_d}\cdot\left(A^{0+}A^1 + A^2 + A^3 + \ldots\right) \end{aligned} \tag{9}$$

Expressing Eq. (9) in the structure adopted in this paper for the BRICS and ROW framework, the Total Intensity Matrix which is presented as the supply chain industrial efficiencies is defined in Eq. (10) as:

$$\text{Supply Chain Industrial Efficiencies} = \underline{e}_d \cdot L = \underline{e}_d \cdot \left(I - \begin{bmatrix} A_{B,B} & A_{B,R} & A_{B,I} & A_{B,C} & A_{B,SA} & A_{B,ROW} \\ A_{R,B} & A_{R,R} & A_{R,I} & A_{R,C} & A_{R,SA} & A_{R,ROW} \\ A_{I,B} & A_{I,R} & A_{I,I} & A_{I,C} & A_{I,SA} & A_{I,ROW} \\ A_{C,B} & A_{C,R} & A_{C,I} & A_{C,C} & A_{C,SA} & A_{C,ROW} \\ A_{SA,B} & A_{SA,R} & A_{SA,I} & A_{SA,C} & A_{SA,SA} & A_{SA,ROW} \\ A_{ROW,B} & A_{ROW,R} & A_{ROW,I} & A_{ROW,C} & A_{ROW,SA} & A_{ROW,ROW} \end{bmatrix} \right)^{-1} \tag{10}$$

Contrarily to the Direct Intensity Matrix in Eq. (8), the Total Intensity Matrix provides a complete assessment of the supply chain efficiency of industries given that a consumption-based perspective (Jakob et al., 2014) is used. This enables a complete visibility of the entire supply chain to be assessed, hence imported goods and services either used indirectly as inputs along supply chains located in other regions or directly as intermediate requirements of a particular industry in the reference country can be captured (Ibn-Mohammed, Greenough, Taylor, Ozawa-Meida, & Acquaye, 2014).

3.3.2. Carbon emissions footprint as a result of final demand

The final demand for goods and services determines the absolute carbon emissions footprint on the environment. Within the Input–Output economic framework, these final demands groups are made up of household's, government, stocks, gross fixed capital formation and exports (West & Jackson, 2015).

Given that $e_d.\boldsymbol{L} = e_d.(\boldsymbol{I}-\boldsymbol{A})^{-1}$ describes the total (direct and indirect) carbon emissions intensity per unit dollar output of an industry (refer to Eqs. (9) and (10)), the carbon emissions footprint in absolute terms as a result of a given demand for goods and services y can be expressed as:

$$Total\, CO_2\, Footprint = \underline{e}_d.\boldsymbol{L}.\underline{y} = \underline{e}_d.(\boldsymbol{I}-\boldsymbol{A})^{-1}.\underline{y} \tag{11}$$

Expressing Eq. (11) in the structure for the BRICS and ROW framework, the total carbon emissions footprint is presented in Eq. (12) as:

$$Total\, CO_2\, Footprint = \begin{bmatrix} E_B & 0 & 0 & 0 & 0 & 0 \\ 0 & E_R & 0 & 0 & 0 & 0 \\ 0 & 0 & E_I & 0 & 0 & 0 \\ 0 & 0 & 0 & E_C & 0 & 0 \\ 0 & 0 & 0 & 0 & E_{SA} & 0 \\ 0 & 0 & 0 & 0 & 0 & E_{ROW} \end{bmatrix} \times \left(I - \begin{bmatrix} A_{B,B} & A_{B,R} & A_{B,I} & A_{B,C} & A_{B,SA} & A_{B,ROW} \\ A_{R,B} & A_{R,R} & A_{R,I} & A_{R,C} & A_{R,SA} & A_{R,ROW} \\ A_{I,B} & A_{I,R} & A_{I,I} & A_{I,C} & A_{I,SA} & A_{I,ROW} \\ A_{C,B} & A_{C,R} & A_{C,I} & A_{C,C} & A_{C,SA} & A_{C,ROW} \\ A_{SA,B} & A_{SA,R} & A_{SA,I} & A_{SA,C} & A_{SA,SA} & A_{SA,ROW} \\ A_{ROW,B} & A_{ROW,R} & A_{ROW,I} & A_{ROW,C} & A_{ROW,SA} & A_{ROW,ROW} \end{bmatrix} \right)^{-1} \times \begin{pmatrix} y_B \\ y_R \\ y_I \\ y_C \\ y_{SA} \\ y_{ROW} \end{pmatrix} \tag{12}$$

3.4. Data sources

The Multi-Regional Input–Output (MRIO) model consisting of the BRICS countries and the ROW region was constructed using both global MRIO tables and environmental data collected from Eora multi-region IO database (Lenzen, Moran, Kanemoto, & Geschke, 2013). The framework as shown in Fig. 2 and Eq. (12) were completed with BRICS's nations data and an aggregation of the ROW data. The Input–Output table in each country includes 25 economic sectors (Refer to Appendix A for the breakdown of industrial sectors). The Eora database contains 20-year of data (1992–2011).

The Input–Output tables are in constant USD prices as these accounts for economic influences such as price changes over time within a country. As such, no price adjustments were made to the tables used in this paper. In terms of price differences across countries, O'Mahony and Timmer (2009) reported that industry-specific Purchasing Power Parities (PPPs), which reflect differences in output price levels across countries, can be used. This price adjustment is often done by means of GDP PPPs, which reflect the average expenditure prices in one country relative to another. It is however well recognised that the use of GDP PPPs, which reflects expenditure prices of all goods and services in the economy, can be misleading when used to convert industry-level output.

3.5. Scope of the study

The choice of the BRICS nations was informed by contemporary ecological economics theory and practice (Daly & Farley, 2011) which highlights the increasing influence of the economic systems of these countries on the natural environment given their rapid economic growth and spending power. For instance, between 1980 and 2013, the share of BRICS based on world merchandise trade rose from 3 to 15% while their share in world GDP trebled from 6 to 19% over the same period. BRICS nations also account for 40% of world population (Nayya, 2016) and it is expected that over the next 50 years, the economies could grow exponentially (Epstein, 2014). There is, therefore, the urgent need for supply chain evaluations, which would provide useful insight into interactions and associated carbon emissions footprint within and among the industrial systems of such countries. In addition, gaining an understanding of the supply chain dependencies and footprint of the BRICS nations with the rest of the global economy is important because environmental impacts are known to leak across geographical boundaries through carbon emissions embodied in goods and services (Paroussos, Fragkos, Capros, & Fragkiadakis, 2015).

The Metal Products industry in the respective countries was chosen to exemplify the assessment processes, because it is one of the heaviest industrial sectors, which received special attention in the recently published Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC 2014).

3.6. Methodological limitations

Despite the methodologically consistent structure offered by economic Input–Output framework, it is known to suffer from a number of limitations. In this study, the most recent data from Eora (Lenzen et al., 2013) is for 2011, highlighting the fact that Input–Output data are not regularly produced. As such, these may not capture significant structural changes and technological advances, which may have taken place within the economy. In addition, Acquaye and Duffy (2010) and Tukker and Dietzenbacher (2013), explained how Input–Output analysis may suffer from inherent limitations because of homogeneity and proportionality assumptions. The homogeneity assumption proposes that each sector produces a uniform product or service output using identical inputs and processes. However, this is obviously not the case since each sector consists of many different products or services. For instance, the Metal Industry consists of different metal products, each of which requires different energy intensities during production. The inherent proportionality assumption resulting from the linearity of input–output equations presumes that inputs to each sector are proportional to their outputs. As such, if the output of a sector (example, the Metal Industry) increases, then the consumption of intermediaries and primary inputs to that sector and

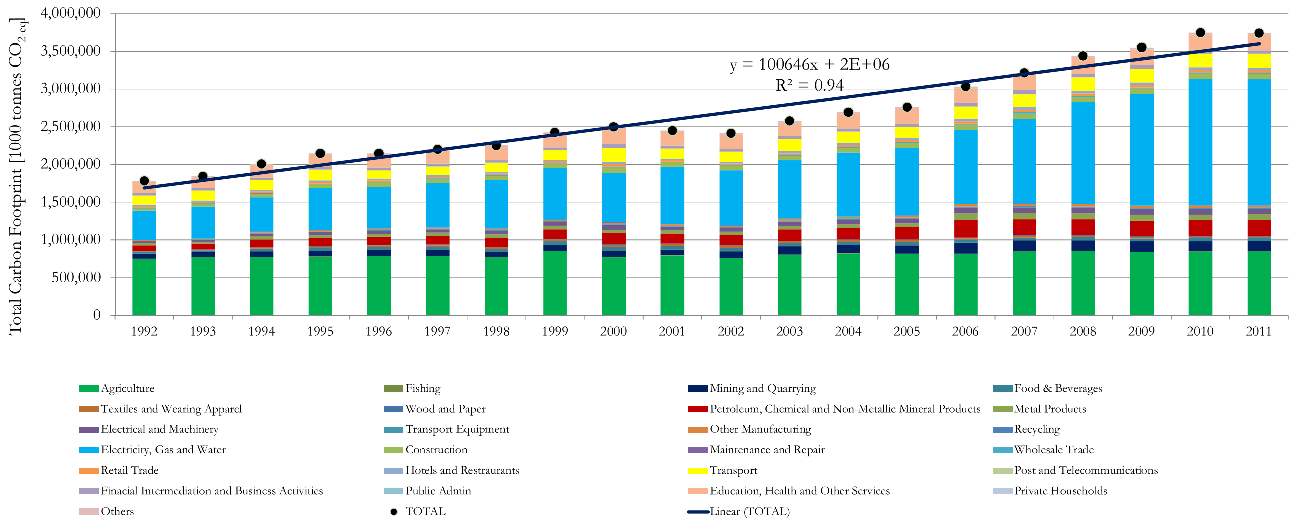


Fig. 3. India's total carbon footprint time series presented as the accumulation of the footprint of each industry.

resultant environmental impacts will also increase proportionally. Economies of scale during production, however, might suggest otherwise.

4. Results and discussions

4.1. Total carbon footprint time series

The evaluation of total carbon footprint over a time series provides a measure of the trends in the total carbon emissions profile driven by final demand for goods and services. This implies that the total carbon emissions of any of the BRICS nations is computed as the domestic carbon emissions produced in that BRICS nation plus the emissions embodied in goods and services that are consumed in that BRICS nation imported into that country. This excludes emissions embodied in BRICS exports. This measurement philosophy conforms with the consumption-based approach to impact assessment, which is deemed more holistic than the production-based approach (Afionis, Sakai, Scott, Barrett, & Gouldson, 2017; Jakob et al., 2014; Takahashi et al., 2014). This is because the consumption-based approach assumes that if the domestic final demand for any goods/services induces carbon in the country of production, then the domestic nation is responsible for those emissions.

In the following, the total carbon footprint time series of each of the BRICS nations are presented. The detailed *heat-map* formatted results are presented in Appendix B. For Brazil, it can be seen that the most dominant sector to the footprint is the Agricultural industry. This is consistent with other findings that suggest that a vast majority of Brazil's carbon emissions is attributed to deforestation (Cerri et al., 2009). This is the result of the Amazon biome in Brazil being used for agriculture purposes and land use through livestock production. Consequently, the demand for agricultural-related products by the final demand group, which averages 95% for domestic households' demand and 4–5% for exports. Further to this, in 2011, it was determined that 92.25% of Brazil's agricultural emissions were the result of domestic demand, with 7.12% due to the ROW and a combined 0.64% due to the other BRICS nations (Russia, India, China and South Africa). For Russia, the Mining and Quarrying, Petroleum, Chemical and Non-Metallic Mineral Products and Electricity, Gas and Water industries are the most dominant in the contribution to the total carbon footprint of the nation. Like the Brazilian economy, the Agricultural industry in India is one of two most important industries that contributes the most to the country's carbon footprint. This is in addition to the Electricity, Gas and Water industry in particular from 2007 onwards. China and South Africa both have the Electricity, Gas and Water industry as the biggest contributor to their nations total carbon footprint over the period considered. It is important to note that these highest contributors to the total carbon footprint have been consistent since 1992.

Table 1
Total carbon footprint trend presented as Equations of Lines of best fit.

BRICS nations	Equation of Line of best fit	R^2 value
Brazil	$y = 10{,}816x + 10^6$	0.1558
Russia	$y = 24{,}282x + 2 \times 10^6$	0.3646
India	$y = 100{,}646x + 2 \times 10^6$	0.9400
China	$y = 411{,}373x + 3 \times 10^6$	0.8927
South Africa	$y = 10{,}992x + 441{,}480$	0.9128

The trend in total carbon footprint also highlights the characteristic emissions profiles of individual sectors from 1992 to 2011 for all the BRICS nations. A linear best-fit equation is also used to characterise the statistical trend of the carbon footprint. Fig. 3 shows the line of best fit for India as an example. Although carbon footprint is not directly a function of time, this statistical trend can, however, provide an indication of how changes in carbon footprint variables (such as final demand or consumption, emissions intensity, energy intensity, etc.) affect the footprint.

Similar to India as shown in Fig. 3, the R^2 value (a statistical measure of how close the data are to the fitted regression line) for China and South Africa are respectively 0.8927 and 0.9128 (Table 1). This is an indication that there is a strong correlation between the carbon emission trends and time in the period between 1992 and 2011 although carbon footprint is not a function of time. Given the positive gradients of the Equation of the Line of Best Fit of these countries, it can be hypothesised that the carbon footprint of these nations will continue to increase over time along the same trajectory if no drastic decarbonisation interventions are implemented.

4.2. Time series analysis of industry-level supply chain efficiencies

In this section, a time series analysis of the supply chain efficiencies (measured as the emissions intensity) of the industries in

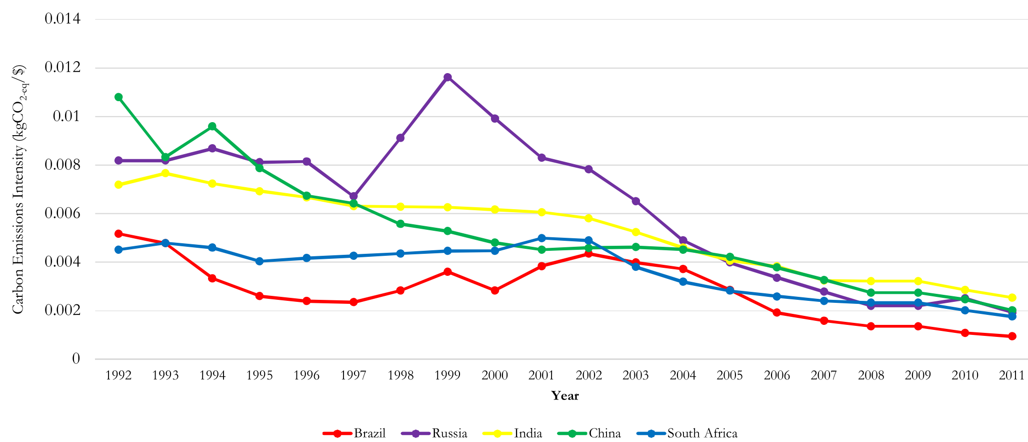


Fig. 4. Time Series Effective Carbon Emissions Intensity of each BRICS nation measured as the weighted average of the intensities of all industries.

each BRICS country is presented (See Fig. 4). The total emissions intensity as presented here is based on both the direct and indirect carbon emissions intensities between 1992 and 2011. To get a full picture of the trends in emissions intensities across the years, these intensities were evaluated as a weighted average of that of each industry in individual BRICS countries.

As shown in Fig. 4, the emissions intensity profile of each country improves from 2004 to 2011 after initial high intensities from 1992 with Russia showing a surge in 1999 with emissions intensity of 0.0116 kilogramCO_2-eq/$. This can be attributed to reduction in economic output. Data from the World Bank (2016) suggests that Russia recorded its lowest Gross Domestic Product in the last 20 years in 1999; hence the observed peak in emissions intensity (measured in terms of kilogramCO_2-eq per $ of economic output) is the result of decreased economic output. Although a general improvement pattern in emissions intensity across the countries is observed, a closer look at the trends between 2004 and 2010 shows that Brazil and Russia experienced a greater decrease in emissions intensities as compared to India, China and South Africa. This is in line with findings by Wu et al. (2015) who examined the relationship between energy consumption, urban population, economic growth and CO_2 emissions in the BRICS countries and reported that economic growth has a decreasing effect on the CO_2 emissions in Brazil and Russia but has an increasing effect in India, China and South Africa. Nevertheless, the improvements in supply chain efficiencies (that is, reduced emissions intensity) of the BRICS countries can be attributed to a number of factors including implementation of robust environmental regulations and policies, energy efficiency programmes and many other decarbonisation initiatives. These signal the intentions of the BRICS nations to reduce their emissions as part of the overall aim of combating climate change at the global level (Bosetti, Carraro, & Tavoni, 2009).

China has taken actions to improve its energy efficiency at both national and local levels. For instance, it has established a 2020 carbon intensity target as part of its national policy and is taking aggressive steps to implement these. These include setting goals for clean energy (such as becoming the leading producer of wind turbines and solar panels) and energy security through its five-year plans (Leal-Arcas, 2013); implementing the Circular Economy paradigm at the core of its thirteenth five-year plan (Mathews & Tan, 2016). Also, as part of the efforts to reduce emissions intensity in India, the government set up the National Action Plan on Climate Change, which entails eight missions including promotion of solar power, energy efficiency improvement, forest coverage and increase in awareness regarding the problems associated with climate change (Shaw, 2013). Brazil, in an attempt to curb its increasing emission values, has committed to reducing its carbon emissions by 36–39%, on its 1990 level, by 2020 under the Kyoto Protocol, whilst setting up a National Climate Change fund for projects focusing on GHG emissions reductions (Shaw, 2013). Similarly, as part of its effort to mitigate climate change, the South-African government (in collaboration with businesses, trade unions and civil society) drafted the National Climate Change Response White Paper which outlines policies, principles and strategies the country will adopt to tackle climate change (EAPSA, 2013).

The emissions intensities across the timeframe considered also highlight the characteristics of the trend in total carbon footprint presented as the cumulative sum of the individual sectors from 1992 to 2011 for all the BRICS nations. As observed from the carbon emissions heat map presented in Appendix C for all the nations, the carbon emissions intensities for each industry has generally tend to decrease since 1992, implying an overall improvement in supply chain efficiencies of its industries (Refer to Appendix C for details of BRICS emissions intensities).

However, a closer look at Fig. 3 shows the total carbon footprint presented as the cumulative sum of the individual sectors for India as an example shows a positive slope, implying an increase in carbon footprint. This opposite relationship or pattern between the emissions intensities and total carbon footprints indicate that final demand for goods and services is increasing in India. The same relationship between emissions intensities and total carbon footprint is observed for China and South Africa (infer from Appendices II and III) although the profile of the total carbon footprints for Brazil and Russia remained relatively constant. This general pattern is again in line with findings of Wu et al. (2015) who asserted that economic growth has a decreasing effect on the CO_2 emissions in Brazil and Russia and has an increasing effect in India, China and South Africa. Following this evidence, we stress that despite a noticeable reduction in emissions intensity (or improvement in supply chain emissions efficiency) which represents a positive step towards addressing carbon emissions issues in the supply chain, the biggest impact towards achieving low carbon supply chains will come from developing strategies that will assist in addressing problems deriving from increasing consumption of goods and services. This is especially relevant given that the rising economic development of these nations will bring about improved economic and social well-being of its residents and lifestyle change, which will lead to increase consumption of goods and services.

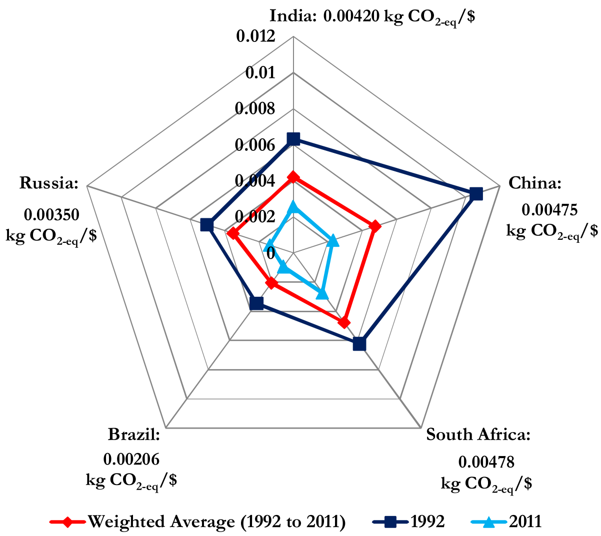


Fig. 5. Weighted average emissions intensities of the Metal Products industry (1992–2011).

4.3. Industry-specific carbon footprint analyses: Metal products industry

To gain insight into low-carbon management in terms of *Industrial Lifecycle Thinking* for a particular industry, an assessment is undertaken in the Metal Products industry of the BRICS nations.

The carbon emissions intensities of the Metal Industry for the BRICS nations are presented in Appendix D. As shown, in 1992 the carbon emissions intensity of the Metal Industries in these countries were higher and relatively more dispersed in terms of range (0.00716 kilogram$CO_{2\text{-eq}}$/$ occurring between China (maximum) and Brazil (minimum)). Over the time, there was constant reduction in the carbon emissions intensities with isolated increases in some years. The most significant increase is Russia in 1999 which can be explained by the reduction in economic output in Russia in 1999 evident by it recording its lowest GDP in the last 20 years in 1999 (World Bank, 2016). It can also be observed that from 2002 heading towards 2011, the carbon emissions intensities are converging within a relatively small range in intensities as compared to 1992 (0.00180 kilogram$CO_{2\text{-eq}}$/$ occurring between South Africa (maximum) and Brazil (minimum)).

Fig. 5 also shows the weighted average of emissions intensities of the metal industry over the years considered. The significantly low average carbon emissions intensities of the Metal Products industry for Brazil, when compared to the other BRICS nations, can be attributed to the low carbon emissions intensity of the electricity industry; a sector on which the Metal Products industry is very much dependent upon.

In 2011 for instance, the carbon emissions intensity of the electricity industry in Brazil was 0.000870 kilogram$CO_{2\text{-eq}}$/$ when compared to 0.00878 kilogram$CO_{2\text{-eq}}$/$ in Russia, 0.0161 kilogram$CO_{2\text{-eq}}$/$ in India, 0.00853 kilogram$CO_{2\text{-eq}}$/$ in China and 0.0205 kilogram$CO_{2\text{-eq}}$/$ in South Africa. The significantly better performance measurement of Brazil's Metal Products industry, which stems from its electricity sector supply chain can be attributed to two factors. First, although Brazil is the 8th largest energy consumer in the world and the third largest in the Americas, behind the United States and Canada, the US Energy Information Administration (2013) recently reported that hydropower (a low carbon source of electricity) accounts for 80% of its total electricity production. Secondly, governmental policies in Brazil such as the effort to improve energy security by addressing the country's dependence on oil imports saw surplus of sugar cane production being channelled to ethanol production and consumption beginning in the 1970 s. As such, Brazil now ranks second largest producer and consumer of ethanol in the world after the United States (US Energy Information Administration, 2013).

The *Industrial Lifecycle Thinking* analysis of the metal products industry was also carried out to determine the step change in carbon emissions footprint over the 20-year time series spanning 1992–2011 in terms of the relative contributions that each country makes to the carbon footprint of the other nations.

From Fig. 6, it can be seen that the carbon footprint of the Metal Products industry for each of the BRICS nations has reduced significantly in the order of 10^3 for all the countries between 1992 and 2011. Two important factors related to the *kaya-like* identity presented in Section 2.2 influences the results in both 1992 and 2011. They are: emissions intensity and product demand. First, despite the fact that the demand for metal products in each of the BRICS nations has increased significantly over the same 20-year period (refer to Fig. 7 where left column represents 1992 demand and right column the 2011 demand), total emissions footprint for the industry in each country has reduced.

In the concluding remarks to Section 4.2, it was reported that the biggest impact towards achieving low carbon supply chains will come from developing strategies that will assist in addressing increasing consumption of goods and services since this is generally the main factor driving up carbon footprint of the BRICS nations. Following this, we submit that for a technology driven industry like the Metal Products industry, which is heavily dependent on the Electricity industry, the gains of improved carbon emissions intensity towards the total carbon footprint would outweigh the increase in the demand of its products. This implies that, despite these increases in the demand and consumption of metal products (Fig. 7), it is in actual fact an improvement in carbon emissions intensity (refer to Fig. 5) that has caused a reduction in the total carbon footprint of the Metal Products industry for these nations (Fig. 6).

The *kaya-like* identity presented in Section 2.2 lists both demand and efficiency improvement as drivers of carbon emissions of an industrial sector. This, therefore, helps to explain the dynamics of the carbon footprint, which is affected by both demand (negatively) and efficiency improvement (positively). For instance, as indicated in Fig. 8, China's demand of metal products increased 15 times, a scenario that would suggest that there should be a corresponding increase in the carbon footprint. However, overall carbon emissions for the industry decreased. The reason for this as stated earlier relates to the overall improvement in the emissions intensity of the metal industry, both globally and within the BRICS countries. These improvements are induced by the implementation of environmental regulations and policies (Serrenho, Mourão, Norman, Cullen, & Allwood, 2016) as well as sector-based emission reductions/preventions schemes using energy efficiency and conservations technologies (Koh et al., 2016). In particular, within the metal industry at the global level, the rates at which metals are recycled have increased. Also, the advent of new and advanced technologies has further reduced the need to extract virgin materials. Technology-based options including the use of cleaner and efficient production processes, end of pipe treatment and efficient waste management and recovery systems have all contributed to the overall improvement in emissions intensity within the sector. Koh et al. (2016) demonstrated cases where technology (i.e., improved efficiency in production systems) directly mitigates emissions.

Napp, Gambhir, Hills, Florin, and Fennell (2014) identified two strategies for emissions reduction in the steel industry, namely: (i) switching to more efficient production routes and (ii) overall

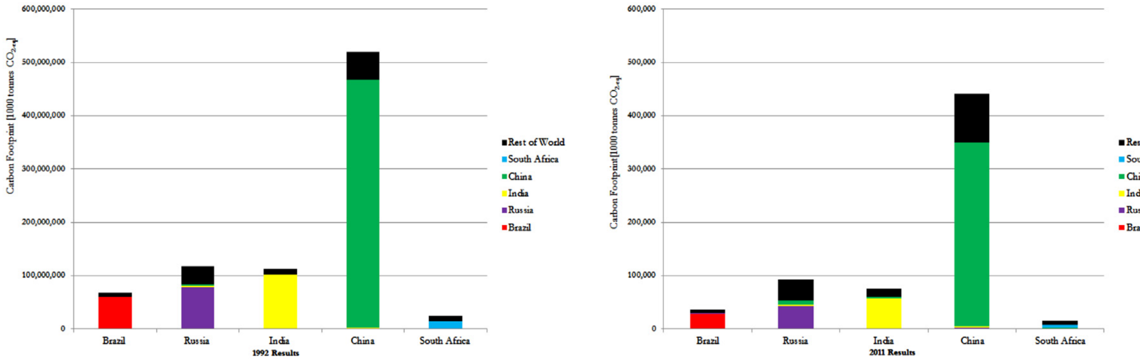


Fig. 6. Change in Carbon Footprint of the Metal Industry in the BRICS nations (1992–2011).

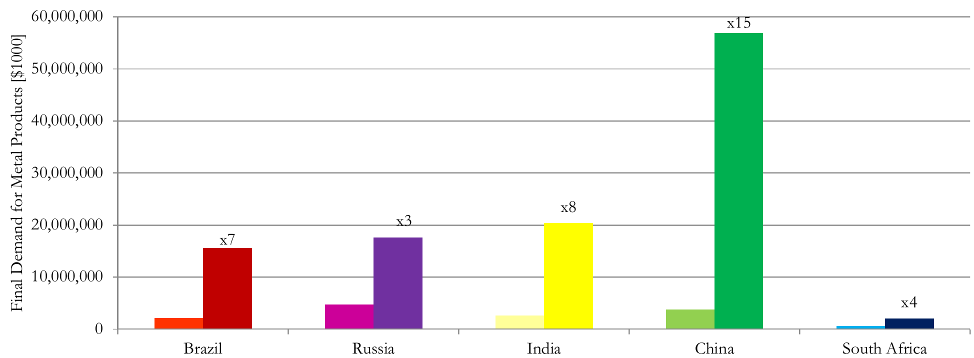


Fig. 7. Change in demand for Metal Products between 1992 and 2011 in the BRICS nations.

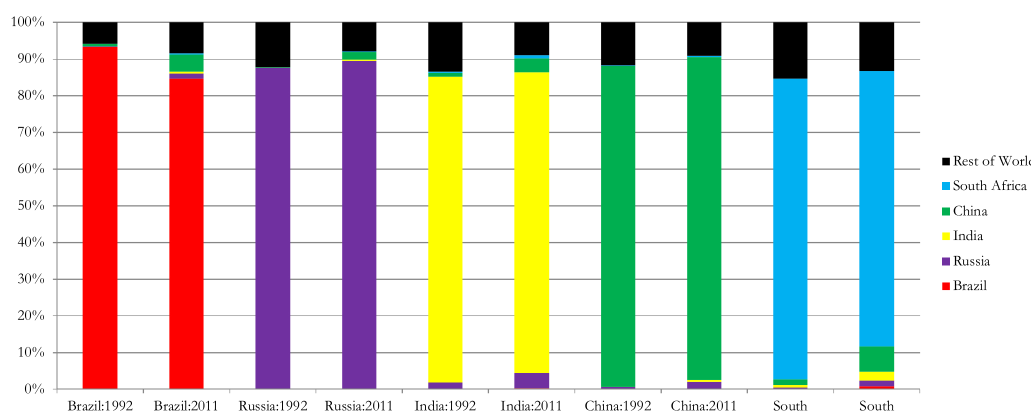


Fig. 8. Percentage Change (between 1992 and 2011) in the source of Carbon Footprint in the Metal Products industry among the BRICS nations and the ROW.

improvements in the efficiency of current manufacturing routes through fuel switching or through the adoption of best available technologies. However, Allwood, Cullen, and Milford (2010) and Gutowski, Sahni, Allwood, Ashby, and Worrell (2013) suggested that a worldwide implementation of efficiency improvements alone is not capable of delivering emissions savings required in the metal industry; as such, material efficiency and demand reduction will also be required. Serrenho et al. (2016) also demonstrated the influence of emissions reduction targets on the emissions of the global steel industry. With respect to the BRICS countries, improvements in emissions intensity and corresponding emissions savings have been largely induced through the use of technologies. For instance, increased basic oxygen furnace (BOF) gas recovery, especially in China and India and the use of coke dry quenching in China, has led to improvements in emissions intensity (Akashi, Hanaoka, Matsuoka, & Kainuma, 2011). In fact, Akashi et al. (2011) concluded that if existing and currently available abatement technologies that cost below $100/tCO_2$ are introduced and implemented within the iron and steel industry by 2030, the projected emissions reduction potential in China and India will be 230 metric tonsCO_2 and 110 metric tonsCO_2 respectively. Overall, the analysis presented so far is in conformity with the trend observed regarding the reduction in emissions despite an increase in demand for metals. This is a clear demonstration of how the use of technologies has led to an overall reduction in toxic emissions in a given industry.

Fig. 8 gives an illustration of the percentage changes in the contributions of carbon emissions footprint among the BRICS nations;

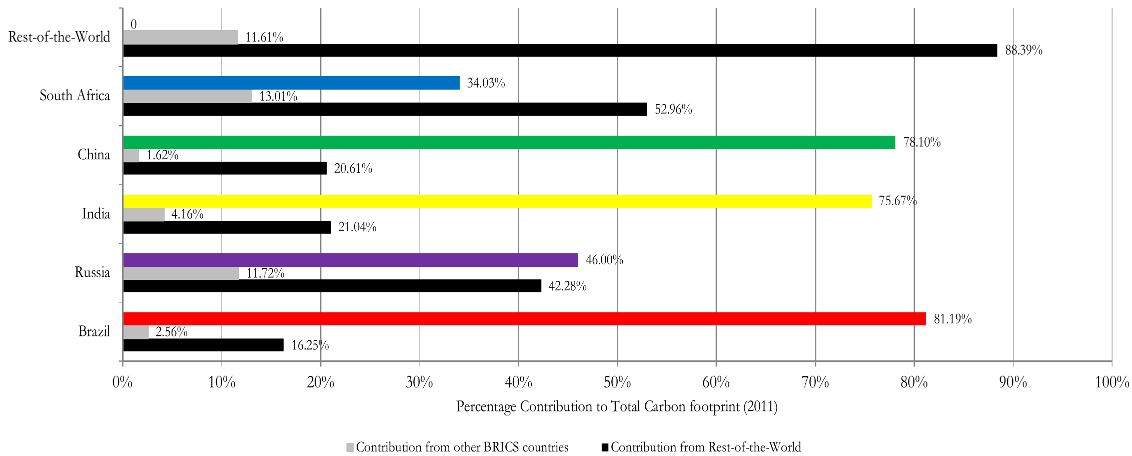


Fig. 9. Imported Carbon Footprint expressed as a percentage of the total due to the demand of metal products by a BRICS nations from the other BRICS nations in 2011.

that is from one country to another between 1992 and 2011 (the 20-year time series period). As a result of the normalisation, what is clearly evident is that although the total carbon footprint has reduced (see Fig. 6), the relative carbon footprint contributions in percentage terms imported from the BRICS nations to another have increased over the period. For instance, the relative carbon footprint of the Metal Products industry of Brazil but imported from China changed from 0.15% in 1992 to 1.83% in 2011. Similarly, the relative carbon footprint of the Metal Products industry in South Africa which is imported from India changed from 2.40% in 1992 to 4.04% in 2011. These incremental percentage changes in carbon footprint can be seen among all the countries as shown in Fig. 8.

This evidence suggests that there has been an increase in the supply chain interaction among the BRICS nations over the last 20 years. This can be explained by the Preferential Trade Theory (Bhagwati & Panagariya, 1996) which suggests that a given economy is bound to provide differentiated treatment to other trade partners on the basis of some variables. The formation of the BRIC in 2008 and expansion to BRICS in 2010 has been the variable that has seen closer economic and trade ties between the BRICS nations as highlighted by Article 20 of the Fortaleza Declaration (BRICS6, 2014).

In terms of *Industrial Lifecycle Thinking*, it follows that the increased trade between the BRICS nations will also result in increased export and import of carbon footprint among these nations; as such there should be concerted efforts to develop collaborative low-carbon supply chain management practices and policies. In fact, as seen in Fig. 9, in 2011, the percentage of carbon footprint related to the Metal Products industry in Brazil, Russia, India, China and South Africa but imported from other BRICS nations are respectively 2.56%, 11.72%, 4.16%, 1.62% and 13.01%. In particular, the results indicate that Russia and South Africa induce significantly high demand of metal products in the other BRICS nations.

In addition, the results for 2011 indicate that the 11.61% of the total carbon footprint for the ROW can be attributed to the BRICS nations. As such, in terms of global efforts to address carbon emissions related impacts, the role of the BRICS nations in efforts to implement low-carbon supply chain management practices on a global scale cannot be ignored.

In terms of carbon emissions embodied in exported goods and services from a BRICS country (induced by demand from other countries) relative to emissions embodied in imported goods and services (induced by the BRICS country in question), the results confirm the findings by Xu and Dietzenbacher (2014) who decomposed global emissions embodied in trade and reported that emerging economies like the BRICS countries have increased their share in production and trade at the expense of developed countries. Thus, they increasingly export more emissions embodied in goods and services than emissions embodied in imported goods and services. In relation to this study, it was determined that for the Metal Industry, the exports emissions relation to the imports are in the following rations for the BRICS nations: Brazil (1.3), Russia (9.9), India (1.5), China (2.1) and South Africa (1.5).

4.4. Impacts of economic growth on carbon footprint

Fig. 10 illustrates the trend in total carbon emissions footprint [1000 tonnes of $CO_{2\text{-eq}}$] and the World Bank's (2015) published Gross Domestic Product or GDP [million $]. The calculated correlation coefficients between total carbon emissions footprint: and GDP are: Brazil (-0.02), Russia (0.84), India (0.97), China (0.94) and South Africa (0.76). With the exception of Brazil, it can be observed that, GDP growth of these nations is highly positively correlated with variations in the carbon footprint of that nation. It is, therefore, to be expected that with the economies of these BRICS nations likely to experience growth, which will account for 30% of the world's GDP, the environmental impacts associated with this growth must be managed. A demonstration of how such management will be realised supported by an evidence-based modelling framework is the hallmark of the current work.

4.5. Supply chain implication of industrial lifecycle thinking

4.5.1. Rethinking the emphasis placed on industrial supply chains

Traditional thinking reiterates the conception that supply chain management is simply the process of managing the delivery of products and services that are important to the consumers (Holweg, Disney, Holmström, & Småros, 2005). However, given the current understanding of the importance of integration (Fawcett & Magnan, 2002), collaboration (Min et al., 2005) and delivering added value following Michael Porter's seminal work on Competitive Advantage (Porter, 1985), supply chain thinking now encapsulates the added value that can be delivered at different levels of the value chain (such as: product-level, process-level, firm-level, enterprise-level and industrial-level). Drawing on from the *industrial lifecycle thinking* approach, which the current work adopts, the complex global supply-chain networks that are interlinked through production and consumption of goods and services (Kagawa et al., 2015) can be assessed from an industrial-level perspective.

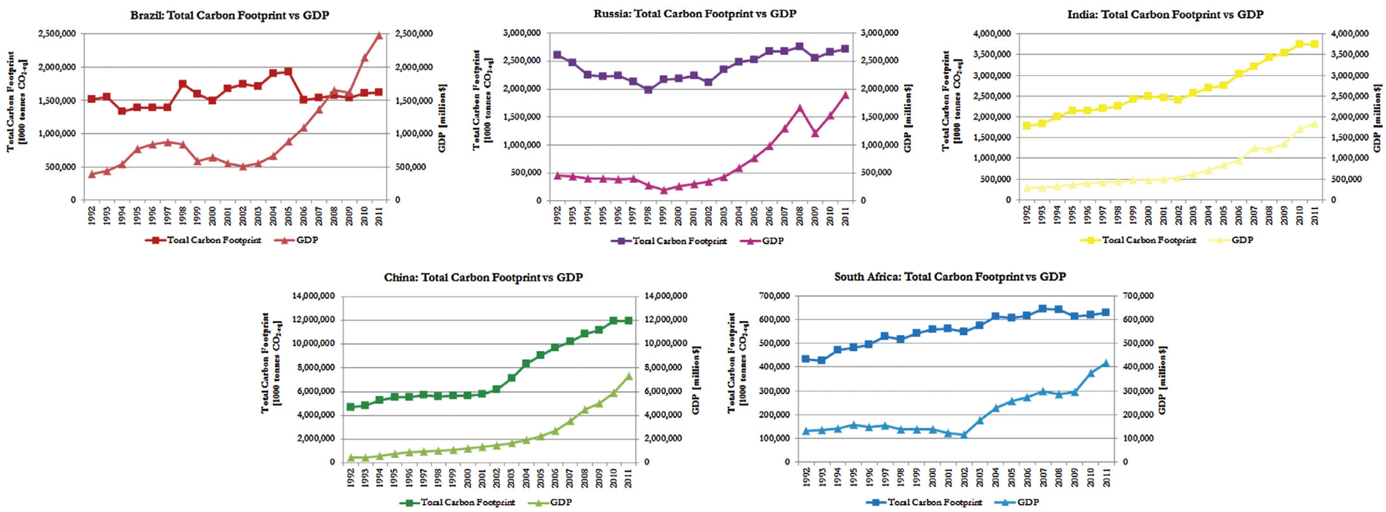


Fig. 10. Carbon Footprint and GDP Trend in the BRICS nations.

4.5.2. Low-carbon supply chain management

Two important reasons (the significance of indirect emissions and opportunity to categorise scope 3 or indirect emissions) underline the importance of measurement and management of supply chain emissions when assessing the influence of industries on the supply chain.

First, the relative significance of indirect emissions cannot be over emphasised. Huang, Weber, and Matthews (2009) identified that Scope 3 or indirect supply chain emissions can account for 75% of total emissions for some organisations and so should not be ignored as knowledge of them can help inform more holistic approaches to address life cycle footprint across the supply chain. Further to this, better knowledge of industry-related indirect emissions can help organisations pursue emissions mitigation projects not just within their own plants but also across their supply chain (Larsen and Hertwich, 2009).

Second, due to the influence of industry supply chains, Huang et al. (2009) reported that businesses can considerably improve on their indirect supply chain emissions capture rates by sector-specific categorisation. This can help identify upstream emission sources that are likely to contribute significantly to different footprints measures as undertaken in this study. This is in addition to specific and general "industry-specific protocols" that can be created by trade organisations.

As previously discussed (in Section 2.2) *industrial level thinking* promotes the complementarity between supply chain assessment and management. As supported by evidence from the paper, the development of low-carbon supply chain management strategies must both lead to a reduction in carbon emissions intensity or improved efficiency (production-side) and reduction in the final demand of goods and services (consumption-side). As a result, two areas of interventions can be identified. First, further improvements in supply chain efficiencies should continue to be pursued by implementing leaner production processes, more efficient and fully optimised transportation and warehousing systems, greener technologies and modern infrastructures that can reduce energy consumption and resource depletion. While requiring some form of upfront investment, such interventions could both result in further improvements in carbon emission intensities and achieve significant cost reductions over time. Such forms of technological advancement and mitigation strategies in supply chains could be favoured by the macro-economic models being implemented by these countries, allowing for high levels of state intervention (Fourcade, 2013). The recent creation of the New Development Bank (Khanna, 2014), a multi-lateral institution operated by BRICS countries whose primary focus is on infrastructural and technological projects (such as investment in renewable energies), could provide further support to these objectives and can also foster better integration and co-operation among the different nations.

Secondly, to modify the demand and consumption patterns as highlighted in this work, re-design of the supply chains and industrial system of the BRICS nations through a paradigm shift, which embraces the policies and principles of the Circular Economy (a production philosophy that pushes the frontiers of environmental sustainability is pertinent (McDonough & Braungart, 2002). Remarkably, the Chinese government has launched a Sustainable Consumption and Production programme inspired by a circular economy paradigm (Yuan, Bi, & Moriguichi, 2006). Such a programme strives to meet resource consumption and waste challenges through supply chains based on cleaner production, industrial ecosystems and life-cycle management. Examples of these approaches include maximising eco-efficiency in the supply chain through resource recovery (Mahlberg & Luptacik, 2014), the implementation of closed-loop supply chains (Devika, Jafarian, & Nourbakhsh, 2014) in which by-products and end-of-life products are reincorporated as raw materials in the production system and tax exemption policies for companies involved in reverse supply chain activities. In this context, the wide experience acquired by the Chinese government and companies in the establishment of supply chains inspired by a circular economy paradigm could be useful to other BRICS nations (Mathews & Tan, 2016).

4.5.3. Carbon emissions embodied in imported goods and services

By adopting a consumption-based approach in this study, the analysis was able to capture the carbon emissions which are induced by the demand for goods and services from a country but are emitted in another country where they are produced. As such these carbon emissions which are embodied in goods and services should be attributed to the inducing (or the importing) country. This process of carbon emissions calculations has been acknowledged as more comprehensive (Barrett et al., 2013; Ibn-Mohammed et al., 2014), although there are concerns and debate as to who is actually responsible for the emissions embodied in goods and services imported into a country (Peters, 2010). In recognition of the integrated and collaborative approach to contemporary supply chain thinking (Beske & Seuring, 2014), this paper accentuates that the formation of the BRICS should bring together a group of nations whose cooperation in low carbon supply chain joint efforts would help to address some of these issues. This is particularly so given that, emissions embodied in imported goods and services from one another country as highlighted in this study are relatively high.

5. Conclusions

This paper adopts an industrial-level perspective towards understanding supply chains at the global level. An environmental sustainability performance model based on an *industrial lifecycle thinking* approach for analysing the carbon footprint of industrial-level supply chains is presented. Using this analytical perspective, a Multi-Regional Input-Output (MRIO) framework was developed and demonstrated in application to the BRICS nations and for the metal Products industries.

In the assessment process, the total carbon footprint and the industrial-level supply chain efficiency expressed as a measure of the carbon emissions intensity was presented for each BRICS country between 1992 and 2011. Across the 25 industrial sectors that constitute the industrial supply chain of each country, it was determined, that over the 20-year period, for India, China and South Africa, there was a very strong linear correlation between the total cumulative carbon footprint and time. It was therefore hypothesised that the carbon footprint of these nations will continue to increase over time given the evidence of the last 20 years by following the same trajectory under a business as usual scenario.

Insight into the industrial-level supply chain efficiency or carbon emissions intensity also pointed to the fact that despite the reduction in emissions intensity (or improvement in supply chain emissions efficiency) of most industries, the cumulative sum of carbon footprint of all industries are increasing. We, therefore, report that despite the reduction in the carbon emissions intensity representing a positive low-carbon mitigation achievement, the biggest impact towards achieving low-carbon supply chains will come from developing strategies that will assist in reducing the consumption of goods and services since this is generally the main factor, which drives up carbon footprint of the BRICS nations. Despite this acknowledgement, an in-depth analysis of the Metal Products industry used as a case study in this paper suggests an exception to this view. This is because, for such a technology driven industry which is heavily dependent on the Electricity industry, the gains of improved carbon emissions intensity towards the total carbon footprint in the Metal Products' industry outweighs the negative effects of the increase in the demand of its products. This is a clear case where the use of technology within an economic sector delivers reduction in carbon footprint.

Further insight into the Metal Products industry suggests that although the total carbon footprint has reduced significantly between 1992 and 2011, the carbon footprint imported from one BRICS nation to another has increased over the same period. This reinforces the fact that there is significant increase in the supply chain interaction among the BRICS nations over the last 20 years. In line with reported integrated and collaborative approach of contemporary supply chain thinking, we accentuate that the formation of the BRICS nations should also be seen as a platform for better cooperation in any low carbon supply chain joint efforts. We also report that given the RoW's Metal Products' industry imported more than 10% of its emissions from the BRICS nations, any global efforts to address carbon emissions related impacts should have these nations central to it.

The paper also provides some insight into the impacts that economic growth can have on the carbon footprint of the BRICS nations. We highlight that given the historical and present positive correlation between total carbon footprint and GDP, the carbon emissions impacts, which will be associated with the BRICS nations who together will account for 30% of the world's GDP will be significant.

Finally, the paper presents some supply chain implications of the study. In particular, it suggests a rethink of the lack of emphasis placed on industrial supply chains in mainstream supply chain management literature. As such, the implications of the study to the higher level supply chains (or industrial-level) which are characterised by increased complexity and added value activities are presented in addition to industrial lifecycle thinking perspective, consumption-based approach to carbon footprint analyses, embodied emissions in goods and services and the need for an integrated and collaborative supply chain cooperation even at the high level of the value chain as highlighted in the case of the BRICS nations.

As part of future research development of this work, the use of Structural Decomposition Analysis within a MRIO can facilitate the understanding of the key drivers of the carbon emissions profile of the BRICS nations.

Appendix A. Breakdown of industrial sectors

1	Agriculture
2	Fishing
3	Mining and quarrying
4	Food & beverages
5	Textiles and wearing apparel
6	Wood and paper
7	Petroleum, chemical and non-metallic mineral products
8	Metal products
9	Electrical and machinery
10	Transport equipment
11	Other manufacturing
12	Recycling
13	Electricity, gas and water
14	Construction
15	Maintenance and repair
16	Wholesale trade
17	Retail trade
18	Hotels and restaurants
19	Transport
20	Post and telecommunications
21	Financial intermediation and business activities
22	Public administration
23	Education, health and other services
24	Private households
25	Others

Appendix B. Total carbon footprint split across industrial sectors [1000 tonnes $CO_{2\text{-}eq}$]

BRAZILTABLE

RUSSIAN INDUSTRIES	Agriculture	Fishing	Mining and Quarrying	Food & Beverages	Textiles and Wearing Apparel	Wood and Paper	Petroleum, Chemical and Non-Metallic Mineral Products	Metal Products	Electrical and Machinery	Transport Equipment	Other Manufacturing	Recycling	Electricity, Gas and Water	Construction	Maintenance and Repair	Wholesale Trade	Retail Trade	Hotels and Restraurants	Transport	Post and Telecommunications	Finacial Intermediation and Business Activities	Public Admin	Education, Health and Other Services	Private Households	Others	TOTAL
1992	178,246.34	27,479.84	397,013.20	91,835.82	5,415.47	5,848.03	534,513.84	57,854.67	34,115.83	912.74	15,343.99	6,493.72	801,003.66	41,540.02	491.80	6,339.04	14,098.34	281.22	282,659.52	388.27	24,037.28	169.77	80,333.61	0.11	30.83	2,606,446.94
1993	179,009.92	27,660.34	376,078.84	87,883.24	4,606.26	5,898.22	504,345.33	57,955.98	28,742.77	1,235.00	14,946.67	6,203.56	763,095.66	32,162.14	569.86	7,344.90	16,336.24	342.46	239,775.06	474.01	29,391.71	238.19	82,781.72	0.18	51.15	2,467,129.42
1994	166,482.01	25,792.75	347,635.82	72,976.77	3,678.16	5,590.37	458,585.99	56,246.72	23,302.82	965.49	13,257.88	5,130.22	714,575.89	21,716.40	463.24	5,970.64	13,279.31	258.70	212,582.02	346.15	23,983.47	182.98	74,561.55	0.15	44.20	2,247,609.70
1995	166,274.92	25,705.25	354,491.84	82,102.17	5,272.46	8,910.31	450,579.57	66,663.48	34,670.80	789.21	15,243.47	6,050.25	658,276.94	30,509.78	463.45	5,973.38	13,285.86	213.55	202,898.29	295.07	23,441.62	146.56	77,210.28	0.14	40.44	2,229,509.08
1996	152,201.42	23,466.00	363,957.50	83,001.85	4,038.86	7,827.28	414,164.35	78,544.05	31,156.90	1,086.21	14,183.31	5,887.36	717,556.03	21,478.96	577.49	7,443.29	16,555.25	242.00	191,516.09	276.63	23,352.75	241.42	74,865.74	0.48	136.50	2,233,757.72
1997	136,321.78	20,996.72	375,424.77	77,299.63	3,769.81	6,526.41	394,711.26	70,796.69	27,540.69	929.09	14,034.71	5,525.82	682,587.45	22,330.03	536.73	6,918.05	15,386.94	233.79	179,393.71	249.69	21,068.75	207.12	73,739.10	0.50	142.23	2,136,671.45
1998	121,077.07	18,666.19	340,825.98	66,306.27	3,788.38	5,592.67	368,068.88	62,554.64	24,680.73	368.90	13,155.71	4,702.75	615,017.82	21,217.45	451.02	5,812.99	12,928.69	219.21	206,917.14	233.65	16,978.12	45.61	71,646.49	0.06	18.00	1,981,274.42
1999	116,519.30	17,931.06	378,321.62	68,522.80	4,019.79	6,081.78	413,702.43	70,997.22	26,677.40	1,021.98	14,243.30	4,983.94	690,818.23	22,483.45	547.55	7,057.24	15,696.24	286.59	218,513.16	301.17	20,190.12	200.14	74,399.42	0.51	145.68	2,173,662.12
2000	117,500.76	18,058.57	393,672.19	72,083.76	4,469.65	6,888.48	433,311.96	76,784.05	30,665.47	341.43	14,681.86	5,266.52	663,822.88	24,047.51	538.85	6,945.08	15,447.04	180.18	204,733.06	122.25	20,979.45	23.48	76,765.09	0.01	2.39	2,187,331.95
2001	120,521.94	18,517.40	405,825.18	74,974.15	4,263.00	6,861.23	436,639.47	76,527.47	30,427.12	1,165.12	15,292.52	5,446.75	675,768.96	23,824.58	561.64	7,238.83	16,100.16	284.56	213,074.15	324.03	21,807.74	249.52	80,228.55	0.73	209.97	2,236,134.75
2002	117,297.88	18,030.56	386,960.30	71,807.08	4,195.75	6,634.82	400,973.30	72,499.67	28,969.17	906.35	14,604.77	5,147.54	634,697.22	22,868.31	479.79	6,183.90	13,753.86	221.98	204,989.20	235.15	18,940.35	184.19	79,233.60	0.49	139.64	2,109,954.86
2003	117,368.54	18,046.61	467,948.12	70,636.82	4,210.09	7,033.21	448,145.25	79,820.97	29,872.00	1,119.33	15,691.37	5,185.26	709,506.34	22,575.78	496.57	6,400.26	14,235.16	246.77	227,684.45	282.21	20,273.83	214.75	83,346.38	0.69	196.67	2,350,537.41
2004	114,625.56	17,611.97	537,196.12	70,780.34	4,081.83	6,809.54	479,660.41	81,512.47	29,981.42	507.90	15,913.45	5,170.05	729,494.11	22,150.48	502.39	6,475.12	14,401.46	246.68	246,113.95	287.75	19,446.38	70.60	84,080.48	0.18	50.95	2,487,171.58
2005	111,354.55	17,094.56	529,680.76	70,852.64	4,259.39	7,139.69	496,273.21	84,004.54	31,417.63	542.44	16,361.81	5,217.69	751,550.01	23,274.77	494.55	6,374.25	14,177.09	162.20	246,040.61	145.53	18,372.62	270.42	85,410.94	0.21	60.49	2,520,532.59
2006	109,206.51	16,739.18	575,604.76	72,721.62	4,502.56	7,712.94	524,389.39	89,418.91	33,437.69	584.19	17,069.17	5,396.42	797,392.86	24,708.45	536.70	6,917.46	15,384.90	171.30	258,542.51	155.09	18,855.28	3,339.17	88,554.25	0.23	66.89	2,671,408.44
2007	107,547.40	16,452.66	615,729.65	76,189.38	4,762.52	8,610.61	514,392.41	95,932.08	36,990.35	619.84	17,832.77	5,703.83	742,050.13	27,580.51	569.08	7,334.93	16,313.96	170.56	259,855.28	156.67	19,218.50	7,220.58	90,847.97	0.24	69.86	2,672,151.74
2008	104,726.51	15,995.31	609,469.96	77,780.80	4,533.94	8,704.16	537,537.03	93,608.32	37,972.74	612.43	18,652.02	5,858.74	798,117.75	29,673.79	573.55	7,392.48	16,442.18	175.97	267,484.27	159.94	20,874.99	9,213.95	95,360.37	0.25	71.50	2,760,992.95
2009	103,435.30	15,799.32	578,150.57	76,642.34	4,535.55	8,496.43	482,868.30	89,995.74	37,144.22	515.06	18,369.64	5,763.31	697,388.92	29,285.41	563.32	7,260.42	16,148.04	156.77	258,420.26	133.91	20,851.91	7,829.70	95,841.96	0.20	58.28	2,555,654.90
2010	102,852.94	15,708.44	592,478.66	76,419.63	4,520.11	8,479.48	515,169.01	90,929.66	37,226.39	499.59	18,227.30	5,737.35	758,140.85	29,432.84	564.64	7,277.52	16,186.93	159.69	262,081.46	134.38	20,494.47	7,870.39	94,082.63	0.19	54.55	2,664,729.10
2011	104,143.74	15,906.79	610,129.59	77,249.34	4,571.52	8,619.57	523,711.89	92,782.50	37,684.49	489.33	18,492.42	5,814.28	772,791.03	29,533.62	570.41	7,351.92	16,351.71	163.89	265,662.21	139.27	20,554.31	8,214.64	94,178.32	0.20	58.05	2,715,165.04

INDIAN INDUSTRIES	Agriculture	Fishing	Mining and Quarrying	Food & Beverages	Textiles and Wearing Apparel	Wood and Paper	Petroleum, Chemical and Non-Metallic Mineral Products	Metal Products	Electrical and Machinery	Transport Equipment	Other Manufacturing	Recycling	Electricity, Gas and Water	Construction	Maintenance and Repair	Wholesale Trade	Retail Trade	Hotels and Restraurants	Transport	Post and Telecommunications	Finacial Intermediation and Business Activities	Public Admin	Education, Health and Other Services	Private Households	Others	TOTAL
1992	749,709.32	885.94	63,612.70	20,137.78	11,305.97	5,436.01	76,769.99	26,960.98	25,614.22	8,326.45	8,214.43	3,540.39	382,725.43	32,785.99	685.73	8,838.50	19,657.35	18,982.39	120,479.07	2,136.97	29,353.34	970.70	146,805.97	61.28	17,586.91	1,781,583.80
1993	766,773.36	880.05	68,649.16	18,895.49	11,432.80	5,009.58	76,705.43	25,447.75	24,443.84	8,327.39	7,963.45	3,419.21	425,057.17	30,432.89	674.18	8,689.49	19,325.97	19,087.24	131,590.68	2,042.62	28,553.11	936.63	138,421.35	58.80	16,874.44	1,839,692.07
1994	769,555.44	914.83	74,443.71	34,814.44	18,648.95	8,824.45	98,257.69	39,468.05	40,089.58	11,264.53	12,152.58	5,717.26	446,725.14	53,076.88	683.99	8,815.97	19,607.68	18,721.33	127,350.71	2,782.77	32,295.59	1,398.96	159,541.42	68.34	19,612.52	2,004,832.82
1995	775,248.02	933.58	78,503.79	34,010.06	18,843.33	8,749.81	102,954.13	39,433.64	40,303.47	11,175.70	12,247.83	5,716.74	554,870.84	52,677.18	697.67	8,992.20	20,000.19	18,884.77	141,061.54	2,872.79	32,956.99	1,418.03	163,133.60	70.02	20,096.02	2,145,851.96
1996	786,880.92	933.05	78,731.96	36,453.00	20,143.61	9,233.25	106,471.01	40,752.64	41,764.82	11,609.13	12,936.38	6,033.07	552,398.00	54,516.72	689.85	8,891.46	19,774.98	18,720.75	112,013.42	2,879.77	32,792.03	1,455.78	166,891.88	69.49	19,943.80	2,142,980.76
1997	784,646.10	943.10	79,504.43	38,071.02	21,422.56	9,807.21	113,812.24	43,466.36	44,414.20	12,518.99	13,519.39	6,395.01	581,106.77	57,331.17	702.42	9,053.44	20,135.59	19,011.85	114,518.46	2,936.57	33,510.40	1,547.61	169,841.49	70.59	20,258.58	2,198,545.55
1998	768,138.20	872.83	73,551.49	35,088.15	20,837.59	9,500.80	115,809.28	47,072.85	44,543.04	12,294.65	13,669.50	6,314.04	642,127.01	57,146.84	680.76	8,774.52	19,516.35	18,609.67	124,714.61	2,786.45	31,754.38	1,576.24	175,693.14	67.60	19,400.67	2,250,540.69
1999	852,842.13	948.98	77,369.99	47,654.46	24,109.23	9,946.29	124,458.70	48,534.52	47,002.11	12,899.86	16,035.12	7,469.14	681,832.28	59,032.91	707.61	9,120.49	20,285.52	18,289.01	129,870.53	2,833.19	32,946.53	1,602.62	179,972.80	70.28	20,171.77	2,426,006.06
2000	770,861.79	1,027.73	85,705.83	49,860.61	26,898.72	10,258.82	142,536.38	47,901.34	53,718.77	13,690.94	22,235.62	7,776.42	653,277.62	69,599.85	1,173.31	15,122.59	33,634.59	27,503.50	181,960.96	3,631.15	46,813.22	1,882.39	196,253.12	107.39	30,820.76	2,494,253.42
2001	794,654.72	961.76	74,956.30	46,584.21	24,196.94	9,653.49	132,171.59	42,396.47	48,017.57	12,396.68	18,450.14	7,093.57	756,403.96	57,799.34	697.74	8,993.05	20,001.31	18,090.91	133,077.15	2,858.08	32,751.26	1,584.69	186,561.28	69.58	19,968.51	2,450,390.30
2002	753,553.19	1,001.27	90,235.60	47,119.91	25,568.59	9,917.63	136,497.38	43,332.49	49,386.35	12,700.48	18,896.27	7,317.70	725,262.99	57,436.22	699.80	9,019.92	20,060.93	18,630.98	138,844.18	2,964.72	33,749.76	1,637.90	187,936.23	71.92	20,641.10	2,412,483.51
2003	800,566.97	1,167.37	111,759.66	43,543.92	22,745.83	6,826.75	150,196.15	45,118.03	56,217.39	14,294.57	20,218.53	6,738.63	770,270.14	58,741.76	879.85	11,340.23	25,222.10	28,273.71	156,086.32	3,854.53	38,417.09	1,430.45	178,963.27	71.54	20,532.02	2,573,476.79
2004	818,963.64	1,182.75	108,686.87	44,437.82	24,324.69	7,768.36	153,751.40	47,428.96	58,743.49	14,628.99	20,710.81	7,032.14	847,804.27	61,036.42	888.47	11,451.85	25,470.08	27,795.80	148,591.58	3,923.27	38,997.87	1,373.99	192,888.62	74.15	21,281.72	2,689,238.02
2005	813,734.27	1,200.28	108,733.08	46,506.95	25,951.08	8,149.18	163,739.23	50,371.10	61,969.89	15,362.59	21,870.13	7,441.50	894,197.82	63,705.06	897.68	11,569.89	25,732.95	28,103.73	145,393.45	3,972.36	39,447.94	1,380.84	195,871.82	74.85	21,481.60	2,756,859.29
2006	814,181.29	1,326.01	144,829.41	38,536.60	19,047.42	9,778.19	230,280.27	93,215.63	77,292.33	15,269.09	26,064.54	8,962.12	975,305.55	70,119.44	1,068.59	13,772.48	30,633.04	33,445.53	158,078.54	5,494.85	43,660.65	1,425.68	194,759.74	82.39	23,645.25	3,030,274.65
2007	844,631.65	1,355.31	145,292.41	38,549.60	17,970.29	9,458.99	215,638.36	80,897.41	76,713.67	15,612.59	25,825.08	8,214.40	1,120,356.65	71,537.96	1,103.10	14,218.11	31,621.77	34,828.98	175,034.93	5,677.03	45,295.21	1,418.76	205,463.14	86.27	24,759.81	3,211,561.46
2008	850,839.67	1,368.06	140,474.05	39,369.26	18,767.62	9,298.13	213,117.76	78,639.23	76,644.04	15,463.41	25,849.25	8,203.62	1,342,117.01	70,926.75	1,085.50	13,991.07	31,118.36	35,385.30	177,018.33	5,529.38	44,662.76	1,386.17	210,649.49	84.80	24,336.18	3,436,325.19
2009	840,581.11	1,365.61	136,780.73	38,662.06	16,999.23	9,144.31	208,645.20	76,638.83	75,453.89	15,202.54	25,678.58	7,858.88	1,480,126.30	71,256.85	1,073.95	13,841.80	30,787.42	35,071.47	176,936.69	5,486.50	44,417.48	1,443.84	210,564.98	84.23	24,174.51	3,548,276.99
2010	842,799.28	1,365.71	137,572.97	38,841.22	17,488.37	9,145.87	210,130.69	76,571.71	75,582.17	15,201.04	25,664.86	7,927.85	1,673,096.01	70,671.72	1,068.92	13,776.62	30,641.61	35,087.48	178,171.49	5,457.97	44,211.72	1,396.25	208,935.33	83.88	24,073.99	3,744,964.71
2011	846,513.79	1,363.31	136,844.00	39,098.63	17,900.52	9,120.10	209,773.99	75,973.98	75,308.81	15,240.71	25,462.79	7,961.50	1,668,513.01	70,432.47	1,064.74	13,722.95	30,522.09	35,114.14	177,850.20	5,437.37	44,148.09	1,380.69	208,834.06	83.53	23,973.30	3,741,638.78

CHINATABLE

SATABLE

Appendix C. Carbon emissions intensities of BRICS nations industrial sectors [kilogramCO_{2-eq}/$]

Brazil [kgCO_{2-eq}/$]	Agriculture	Fishing	Mining and Quarrying	Food & Beverages	Textiles and Wearing Apparel	Wood and Paper	Petroleum, Chemical and Non-Metallic Mineral Products	Metal Products	Electrical and Machinery	Transport Equipment	Other Manufacturing	Recycling	Electricity, Gas and Water	Construction	Maintenance and Repair	Wholesale Trade	Retail Trade	Hotels and Restraurants	Transport	Post and Telecommunications	Finacial Intermediation and Business Activities	Public Administration	Education, Health and Other Services	Private Households	Others
1992	0.029278072	0.0314803	0.0069792	0.015405	0.0033066	0.0040263	0.0051676	0.0034695	0.002458	0.0028813	0.002116568	0.0021166	0.0024518	0.002128169	0.000931116	0.0009311	0.0009311	0.008134594	0.0065043	0.0017229	0.0006861	0.001201	0.0015375	0.009333578	0.0093338
1993	0.030483992	0.0320104	0.0070863	0.0146406	0.0027764	0.0035874	0.0048488	0.0031366	0.0021759	0.0025813	0.001844885	0.0018449	0.0021651	0.001762862	0.000750208	0.0007502	0.0007502	0.00699321	0.0063461	0.0015092	0.0004623	0.0009019	0.0012733	0.008318568	0.0083184
1994	0.01773786	0.0257608	0.005832	0.0090584	0.0020303	0.0025009	0.0039725	0.002636	0.001873	0.002209	0.001450762	0.0014508	0.0017228	0.001438294	0.000603496	0.0006035	0.0006035	0.004478968	0.0052641	0.0011961	0.0003142	0.0006627	0.0009351	0.006102013	0.0061018
1995	0.015306209	0.0209168	0.0041405	0.007445	0.0015483	0.0017408	0.0030105	0.002088	0.0015218	0.0017181	0.001148059	0.0011481	0.0014016	0.001141233	0.000475751	0.0004758	0.0004757	0.003470213	0.0041783	0.0008839	0.0002468	0.0005052	0.0006819	0.004238143	0.0042383
1996	0.014133519	0.0183045	0.0036193	0.006822	0.0014127	0.0015683	0.0027747	0.0019131	0.0014064	0.0015835	0.001053896	0.0010539	0.0013215	0.001034186	0.000422221	0.0004222	0.0004222	0.003084312	0.0039702	0.0007702	0.0002193	0.000433	0.0006177	0.003839968	0.0038399
1997	0.013768606	0.0173055	0.0034053	0.0065948	0.0013688	0.0015064	0.0027467	0.001838	0.0013519	0.0015517	0.001033107	0.0010331	0.0013454	0.00103066	0.000401866	0.0004019	0.0004019	0.002893448	0.0039383	0.0007093	0.0002072	0.0003989	0.0005987	0.003527014	0.0035271
1998	0.018641978	0.0182157	0.0032997	0.008878	0.0016324	0.0018478	0.0029143	0.0018488	0.0013918	0.0016197	0.001155909	0.0011559	0.0014428	0.001051694	0.000411461	0.0004115	0.0004115	0.003798973	0.0040863	0.0007136	0.0002253	0.0004376	0.0006283	0.003154789	0.0031549
1999	0.022029973	0.0252191	0.0048534	0.0106452	0.0021427	0.0023775	0.0038828	0.0025539	0.0018612	0.0021338	0.00158133	0.0015814	0.0024181	0.001468174	0.000577405	0.0005774	0.0005774	0.00461258	0.005627	0.0009651	0.0003109	0.0005789	0.0008594	0.00439839	0.0043984
2000	0.015375594	0.0224925	0.0047545	0.0077558	0.0019288	0.002054	0.0036068	0.0025434	0.0017996	0.0020594	0.001546327	0.0015463	0.0024246	0.001558002	0.000601631	0.0006016	0.0006016	0.003569313	0.0047571	0.0008714	0.0003418	0.0005337	0.0008196	0.002964937	0.0029649
2001	0.022822588	0.0278215	0.0052428	0.0114488	0.0025239	0.0026646	0.0043406	0.0028423	0.0021111	0.0023859	0.001908221	0.0019082	0.0029648	0.001783946	0.000668256	0.0006682	0.0006683	0.005076689	0.0059191	0.0010644	0.0004196	0.0006935	0.0010017	0.00368635	0.0036864
2002	0.026775269	0.0319685	0.0058405	0.0131976	0.0027856	0.0029911	0.0047004	0.003179	0.0023109	0.0026038	0.002082056	0.002082	0.0030432	0.001954035	0.000729664	0.0007297	0.0007297	0.0058394	0.0065348	0.0011756	0.0004638	0.0007729	0.0011069	0.004126463	0.0041265
2003	0.020505768	0.0293974	0.0054961	0.0114606	0.0026133	0.0027784	0.0044227	0.0030351	0.0022377	0.002517	0.00194646	0.0019464	0.0029032	0.001879333	0.000703195	0.0007032	0.0007032	0.005332304	0.006052	0.0011222	0.0004478	0.0007703	0.0010811	0.003990871	0.0039908
2004	0.019368079	0.0256451	0.0047443	0.0108176	0.0025637	0.0026038	0.0039032	0.0027793	0.0020369	0.0023069	0.001759705	0.0017597	0.0026687	0.001673993	0.000639422	0.0006394	0.0006394	0.005056131	0.0053026	0.0010072	0.0004103	0.0007228	0.0010074	0.0036364	0.0036364
2005	0.014446101	0.0194641	0.0036805	0.0081345	0.0020209	0.0020405	0.0031023	0.0021827	0.0016506	0.0018789	0.001397008	0.001397	0.0021349	0.001328171	0.000504811	0.0005048	0.0005048	0.00382596	0.0041978	0.0008004	0.0003247	0.0005665	0.0007865	0.002729022	0.0027291
2006	0.007379615	0.015241	0.0028415	0.0044523	0.0014022	0.0014362	0.0024877	0.0018203	0.0014095	0.0015987	0.00112439	0.0011244	0.0017535	0.001067542	0.000383608	0.0003836	0.0003836	0.002118516	0.0035005	0.0006447	0.0002466	0.0003977	0.0005861	0.002142101	0.0021421
2007	0.006136385	0.0124648	0.0023048	0.0037158	0.001157	0.0012211	0.0021	0.0015377	0.0012049	0.0013761	0.000933556	0.0009336	0.0014281	0.000898179	0.000321838	0.0003218	0.0003218	0.001751869	0.0029979	0.0005439	0.000207	0.0003285	0.000484	0.001734851	0.0017349
2008	0.005120962	0.0104971	0.0019269	0.0031009	0.0009649	0.0010282	0.0018361	0.0013314	0.0010416	0.0011923	0.000793107	0.0007931	0.0012401	0.000785164	0.000288668	0.0002887	0.0002887	0.001475492	0.0025138	0.0004647	0.000179	0.0002853	0.0004187	0.001467107	0.0014671
2009	0.005175489	0.0106207	0.0019097	0.0031353	0.000954	0.0010136	0.0018496	0.001319	0.0010348	0.0011963	0.000790858	0.0007909	0.0012143	0.000777239	0.000276213	0.0002762	0.0002762	0.001478849	0.0023859	0.0004444	0.0001722	0.0002799	0.0004159	0.001458883	0.0014589
2010	0.004002224	0.0081499	0.0015232	0.0024795	0.0007785	0.0008221	0.0014884	0.0010794	0.0008584	0.0009906	0.000648242	0.0006482	0.0009926	0.000634367	0.000236175	0.0002362	0.0002362	0.001186715	0.0021141	0.0003839	0.000145	0.0002341	0.0003432	0.001144188	0.0011442
2011	0.003478944	0.0070811	0.0013174	0.0021685	0.0006837	0.0007205	0.0012968	0.0009396	0.0007496	0.0008649	0.000566665	0.0005667	0.0008705	0.000554482	0.000206467	0.0002065	0.0002065	0.001041198	0.0018363	0.0003356	0.0001275	0.0002054	0.0003005	0.000996382	0.0009964

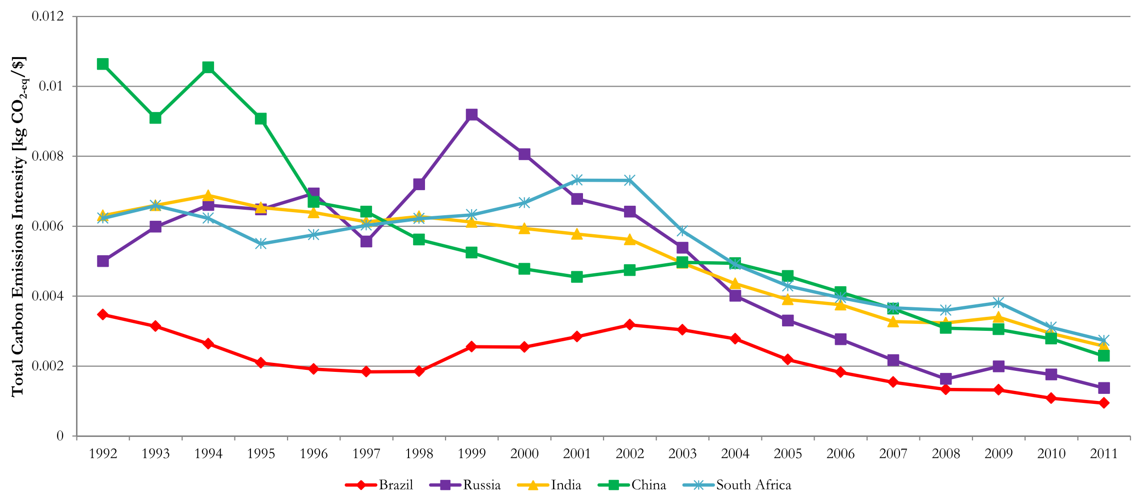
Russia [kg CO_{2-eq}/$]	Agriculture	Fishing	Mining and Quarrying	Food & Beverages	Textiles and Wearing Apparel	Wood and Paper	Petroleum, Chemical and Non-Metallic Mineral Products	Metal Products	Electrical and Machinery	Transport Equipment	Other Manufacturing	Recycling	Electricity, Gas and Water	Construction	Maintenance and Repair	Wholesale Trade	Retail Trade	Hotels and Restraurants	Transport	Post and Telecommunications	Finacial Intermediation and Business Activities	Public Admin	Education, Health and Other Services	Private Households	Others
1992	0.0078021	0.00786	0.036874	0.0066122	0.004987	0.003911	0.0116518	0.0050028	0.0040831	0.012727	0.006297563	0.005819	0.0633958	0.004147568	0.0018211	0.0018212	0.0018211	0.008025873	0.0077319	0.0085632	0.0031483	0.0141475	0.0059196	0.030057837	0.0300576
1993	0.0088711	0.0089401	0.0381191	0.0074748	0.0057469	0.004766	0.0123676	0.005985	0.0046913	0.016998	0.007171539	0.0066453	0.0636528	0.004655013	0.0020598	0.0020598	0.0020598	0.009517484	0.0078982	0.010829	0.0037026	0.0198958	0.0066994	0.047833807	0.0478332
1994	0.0095122	0.0095964	0.0382218	0.0077383	0.0063021	0.0052988	0.0129455	0.0066026	0.0049594	0.0144544	0.007652651	0.0070205	0.0662814	0.004781371	0.0020705	0.0020705	0.0020705	0.009204724	0.0081909	0.0099964	0.0038455	0.0170284	0.0070665	0.041326837	0.0413268
1995	0.008912	0.0089743	0.0350417	0.0075928	0.0059602	0.005278	0.0118824	0.0064814	0.0049063	0.0118285	0.007394825	0.0069356	0.0566579	0.004687602	0.0019863	0.0019863	0.0019863	0.008137703	0.0074629	0.0083649	0.0036002	0.0136677	0.0065864	0.03735661	0.0373572
1996	0.0086018	0.0086577	0.030863	0.0075351	0.0055617	0.0052206	0.0118697	0.0069361	0.0048878	0.0122164	0.007452325	0.0069294	0.0506769	0.004358186	0.0019914	0.0019913	0.0019914	0.014745342	0.0075054	0.0137789	0.0036139	0.0131321	0.0065189	0.030233187	0.0302332
1997	0.006854	0.0068891	0.0254615	0.0061859	0.0045655	0.0041536	0.0094772	0.0055604	0.00402	0.0101152	0.006145923	0.0056162	0.0409498	0.003679356	0.0017644	0.0017644	0.0017644	0.01206882	0.006113	0.0112685	0.0029602	0.0104026	0.005514	0.023604051	0.0236044
1998	0.0086813	0.0087366	0.0304611	0.0076492	0.0053373	0.0051927	0.0126266	0.0071962	0.0049643	0.0090379	0.007929186	0.006947	0.0558678	0.004689411	0.002446	0.002446	0.0024461	0.014919866	0.0092451	0.0130377	0.0037363	0.006829	0.007217	0.005248659	0.0052487
1999	0.0106387	0.0106979	0.0370274	0.009541	0.0064526	0.0065477	0.0160677	0.0091885	0.0063648	0.0125517	0.010068814	0.0086579	0.070184	0.006156262	0.0034385	0.0034385	0.0034385	0.018095603	0.0117723	0.0152391	0.0050282	0.012015	0.0095076	0.026131163	0.0261303
2000	0.0091388	0.0091801	0.0335056	0.0083645	0.0056757	0.0058149	0.0142723	0.0080551	0.0056477	0.0099865	0.008730113	0.0076374	0.0584691	0.005328533	0.0027045	0.0027045	0.0027045	0.014509227	0.0096663	0.0124651	0.0042427	0.0076576	0.0079938	0.00304501	0.003045
2001	0.0076987	0.0077264	0.0291985	0.0071779	0.005048	0.0049432	0.0118187	0.0067784	0.0048588	0.0108322	0.007404166	0.0065288	0.0477317	0.004561871	0.0023573	0.0023573	0.0023573	0.013494212	0.0081829	0.0120774	0.0036635	0.0110105	0.0068113	0.027165644	0.0271648
2002	0.0072161	0.0072445	0.0285458	0.0066808	0.0048033	0.0046751	0.011116	0.0064147	0.0044872	0.0097861	0.006994726	0.0061213	0.0461482	0.004160577	0.0020713	0.0020712	0.0020713	0.012811028	0.0077969	0.0115655	0.0032958	0.0092501	0.006314	0.019962664	0.0199621
2003	0.0058364	0.0058587	0.0249109	0.0054134	0.0041289	0.003951	0.0092928	0.0053854	0.0038018	0.0081943	0.005856875	0.0050259	0.0378439	0.003537412	0.0017702	0.0017702	0.0017702	0.010370338	0.0065853	0.0094829	0.0028572	0.0087807	0.0053408	0.018087011	0.0180872
2004	0.0042522	0.0042637	0.0196087	0.004035	0.0032088	0.0029548	0.0070433	0.0040074	0.0028645	0.0051845	0.004356542	0.0037436	0.0277462	0.002672989	0.0013532	0.0013531	0.0013531	0.007643328	0.0050461	0.0070896	0.0021435	0.00545	0.0039716	0.004366338	0.0043663
2005	0.0033811	0.0033864	0.0159275	0.003282	0.0027018	0.0024517	0.0057932	0.0033039	0.002394	0.0044935	0.003583081	0.0030639	0.0226688	0.002214494	0.0011059	0.0011059	0.0011059	0.006235224	0.0040749	0.0057194	0.0017539	0.0076789	0.0032507	0.004098471	0.0040985
2006	0.0027559	0.0027558	0.0132281	0.0027567	0.0023512	0.0020767	0.0048367	0.0027653	0.0020188	0.0040358	0.003000453	0.0025789	0.0188767	0.001873109	0.0009313	0.0009313	0.0009313	0.005351455	0.0034053	0.0050099	0.0014618	0.0258242	0.0027001	0.003579748	0.0035797
2007	0.0021355	0.0021306	0.0109097	0.0022272	0.0018448	0.0016238	0.0036812	0.0021708	0.0015865	0.0034993	0.002334854	0.0020681	0.0137719	0.001458315	0.0007166	0.0007166	0.0007166	0.004260843	0.0026224	0.0041109	0.0011214	0.0370696	0.0020501	0.003178815	0.0031788
2008	0.0015686	0.0015635	0.0079664	0.001665	0.0013855	0.0012425	0.002767	0.0016331	0.0012376	0.002825	0.001775619	0.001553	0.0104289	0.001145112	0.0005601	0.0005601	0.0005602	0.003304007	0.0019787	0.003249	0.0008811	0.033221	0.0015824	0.002496037	0.002496
2009	0.0019445	0.0019394	0.0101572	0.0020397	0.0016146	0.0014799	0.0033411	0.0019906	0.001467	0.0034019	0.002167057	0.0018888	0.012491	0.001357595	0.0006693	0.0006693	0.0006693	0.003968315	0.002486	0.0039157	0.0010591	0.0373867	0.0019151	0.002903045	0.0029031
2010	0.0016941	0.0016891	0.0090021	0.0017885	0.0014484	0.0013239	0.0030219	0.0017585	0.0013108	0.0030848	0.001919201	0.0016631	0.0115665	0.001214046	0.0005901	0.0005901	0.0005901	0.003603672	0.0021833	0.0035461	0.0009442	0.0323652	0.0017053	0.002490152	0.0024902
2011	0.0013276	0.0013229	0.007026	0.001416	0.001142	0.0010362	0.0023159	0.0013726	0.0010415	0.002469	0.001492277	0.00131	0.008781	0.000965161	0.0004779	0.0004779	0.0004779	0.002786562	0.0016841	0.0027458	0.0007453	0.0255689	0.0013301	0.002046528	0.0020465

India [kg CO_{2-eq}/$]	Agriculture	Fishing	Mining and Quarrying	Food & Beverages	Textiles and Wearing Apparel	Wood and Paper	Petroleum, Chemical and Non-Metallic Mineral Products	Metal Products	Electrical and Machinery	Transport Equipment	Other Manufacturing	Recycling	Electricity, Gas and Water	Construction	Maintenance and Repair	Wholesale Trade	Retail Trade	Hotels and Restraurants	Transport	Post and Telecommunications	Finacial Intermediation and Business Activities	Public Admin	Education, Health and Other Services	Private Households	Others
1992	0.0112857	0.0008197	0.0090953	0.0086668	0.0065536	0.0053199	0.0079148	0.0063039	0.0055167	0.0062215	0.005867438	0.0069142	0.0282445	0.004535666	0.0015767	0.0015767	0.0015767	0.008880216	0.0080529	0.0014347	0.0018381	0.0001641	0.0115217	0.00278862	0.0027886
1993	0.0115761	0.0008273	0.0096896	0.0089343	0.0068223	0.0055838	0.0083142	0.0065952	0.0057774	0.0064614	0.006130746	0.0072056	0.0313252	0.004729799	0.0016309	0.001631	0.0016309	0.009078387	0.0086151	0.0015822	0.001884	0.0001716	0.0115394	0.002882051	0.002882
1994	0.0104099	0.000835	0.0096636	0.008757	0.0068087	0.0055697	0.0082379	0.0068796	0.0061077	0.0067152	0.006383267	0.0071728	0.0288175	0.004913384	0.0014819	0.0014819	0.0014819	0.008273348	0.0080733	0.0015596	0.0017744	0.000221	0.0102683	0.002811785	0.0028118
1995	0.0093266	0.0007883	0.009054	0.0078412	0.0063618	0.0052343	0.0078405	0.0065339	0.0057216	0.0064197	0.005923631	0.0066456	0.0310454	0.004620649	0.0014406	0.0014406	0.0014406	0.007557944	0.0081303	0.0015561	0.0016719	0.0002166	0.0094204	0.002660669	0.0026607
1996	0.0090099	0.0007609	0.0087564	0.007691	0.006261	0.0051229	0.0077009	0.0063923	0.005627	0.006292	0.005815273	0.006516	0.0297026	0.004502788	0.0013678	0.0013678	0.0013678	0.007248981	0.0073413	0.0015033	0.0016043	0.0002047	0.0091042	0.002563999	0.002564
1997	0.0083488	0.0007204	0.0080959	0.0072366	0.0059506	0.0049086	0.0073886	0.0061261	0.0054149	0.0060542	0.005588401	0.0061927	0.0285205	0.004308449	0.0012961	0.0012961	0.0012961	0.006783678	0.0069916	0.0014249	0.0015179	0.0002005	0.008568	0.002435024	0.002435
1998	0.0080121	0.0006702	0.0075626	0.0070428	0.0058715	0.0048559	0.007422	0.0062796	0.0055461	0.0061187	0.005628114	0.0061496	0.0302421	0.004265332	0.0012701	0.0012701	0.0012701	0.006324986	0.0071549	0.0014023	0.0014393	0.0001958	0.0084207	0.002352491	0.0023525
1999	0.008163	0.00071	0.0073604	0.007135	0.005853	0.0047425	0.0073255	0.0061178	0.0053576	0.0059865	0.005699781	0.0061639	0.0300134	0.004172777	0.0012385	0.0012385	0.0012385	0.006507331	0.0071382	0.0013646	0.0014218	0.0001873	0.0081765	0.002318017	0.0023181
2000	0.0075196	0.0007652	0.0072991	0.0068846	0.0057288	0.0046636	0.0074144	0.005934	0.0054828	0.0059156	0.006321386	0.0059411	0.0272003	0.004363172	0.0014976	0.0014975	0.0014976	0.006894609	0.0075207	0.0014351	0.0016026	0.0002142	0.0087379	0.002786777	0.0027868
2001	0.0072663	0.000693	0.0068981	0.0065379	0.0056118	0.0045865	0.007298	0.0057743	0.0052552	0.0058425	0.005776729	0.0057843	0.0312126	0.00404901	0.0012196	0.0012196	0.0012195	0.00603074	0.0071677	0.0013734	0.0013613	0.0001836	0.0080419	0.002264	0.002264
2002	0.0067301	0.0006826	0.0067455	0.0061957	0.0053673	0.0044108	0.0071505	0.005621	0.0050824	0.0056316	0.005597617	0.005542	0.0293171	0.003933744	0.0011829	0.001183	0.0011829	0.005753615	0.0069916	0.0013314	0.0013207	0.0001812	0.0078999	0.002215499	0.0022155
2003	0.0063473	0.0006776	0.0066761	0.0055014	0.0053673	0.0038589	0.0062807	0.004948	0.004528	0.0050059	0.004968671	0.0049298	0.0254609	0.003556311	0.0012356	0.0012356	0.0012356	0.005395474	0.005995	0.0014325	0.001329	0.0001627	0.0073178	0.002282682	0.0022868
2004	0.00542	0.0005863	0.0057088	0.0047612	0.0041302	0.0033252	0.005487	0.0043586	0.0039475	0.0044563	0.004307838	0.0043068	0.0231429	0.003105214	0.0010712	0.0010712	0.0010712	0.0047541	0.005311	0.0012483	0.0011488	0.0001333	0.0064414	0.001930734	0.0019307
2005	0.0046437	0.0005204	0.0049236	0.0041562	0.0036514	0.002967	0.0049088	0.0039034	0.0035366	0.003993	0.003859826	0.0038114	0.0209166	0.002772846	0.0009497	0.0009497	0.0009497	0.004139681	0.0046997	0.0011124	0.0010116	0.0001168	0.0056357	0.001711627	0.0017116
2006	0.0044141	0.0005955	0.0044152	0.0036915	0.0034549	0.0027737	0.0044299	0.0037535	0.0034576	0.0037061	0.003737066	0.0035928	0.0190881	0.002777899	0.001004	0.001004	0.001004	0.003899506	0.0042805	0.001293	0.0010613	0.0001202	0.0053143	0.001940265	0.0019403
2007	0.0036103	0.0004789	0.0038088	0.0030726	0.0028575	0.002427	0.0037926	0.0032725	0.0029214	0.0031688	0.003135735	0.0030772	0.0166774	0.002339433	0.0008425	0.0008425	0.0008425	0.003280618	0.0037163	0.001084	0.0008799	9.919E-05	0.0044215	0.001605104	0.0016051
2008	0.003348	0.0004425	0.0036205	0.0028717	0.0027365	0.0023373	0.0036888	0.003238	0.0028306	0.003146	0.002991203	0.0029697	0.0186617	0.002259275	0.0008087	0.0008087	0.0008087	0.003131129	0.0037628	0.0010391	0.0008263	9E-05	0.0041522	0.001503511	0.0015035
2009	0.0032956	0.0004512	0.0036391	0.0028751	0.0027973	0.0024302	0.0038131	0.0034	0.0029772	0.0033121	0.003129272	0.0030643	0.020274	0.002337936	0.0008307	0.0008307	0.0008307	0.003148482	0.0039462	0.0010808	0.0008415	9.354E-05	0.0040812	0.001558241	0.0015582
2010	0.0026848	0.0003848	0.0030234	0.0023793	0.0023664	0.0020925	0.0032454	0.0029295	0.0025521	0.0028624	0.002662192	0.0026067	0.018223	0.001998312	0.0007144	0.0007143	0.0007143	0.002624306	0.0034192	0.0009348	0.0007173	8.114E-05	0.0033249	0.001324299	0.0013243
2011	0.0023964	0.0003463	0.0026885	0.0021179	0.002096	0.0018526	0.0028595	0.0025717	0.0022258	0.0025123	0.002316502	0.0023027	0.0161338	0.001771655	0.0006423	0.0006423	0.0006423	0.002339777	0.0030269	0.0008345	0.0006449	7.301E-05	0.0029586	0.001172295	0.0011723

China [kg CO_{2-eq}/$]	Agriculture	Fishing	Mining and Quarrying	Food & Beverages	Textiles and Wearing Apparel	Wood and Paper	Petroleum, Chemical and Non-Metallic Mineral Products	Metal Products	Electrical and Machinery	Transport Equipment	Other Manufacturing	Recycling
1992	0.0126309	0.0034651	0.0156069	0.0092603	0.0093403	0.0074827	0.0124216	0.0106319	0.007612	0.0072216	0.008974136	4.374E-05
1993	0.0106518	0.0032895	0.0134892	0.0076447	0.0068508	0.0069672	0.0109276	0.0090899	0.0063834	0.0061063	0.007461054	3.64E-05
1994	0.0119752	0.0037256	0.0161668	0.0086688	0.0079192	0.0079693	0.0128572	0.0105403	0.0071462	0.0068833	0.008670285	3.571E-05
1995	0.0099008	0.0032862	0.0131744	0.0072114	0.0064913	0.0066085	0.0104116	0.0090682	0.0059935	0.005829	0.00714383	2.725E-05
1996	0.0085256	0.003532	0.0099734	0.0064357	0.0062054	0.0053677	0.0094394	0.0066894	0.0047518	0.0046986	0.006093804	2.439E-05
1997	0.0077918	0.0032958	0.0095669	0.0060062	0.00582	0.0050924	0.0091094	0.0064133	0.0044991	0.0044297	0.005764878	1.833E-05
1998	0.0074379	0.0029456	0.0079397	0.0051456	0.0051245	0.0041693	0.0079128	0.0056145	0.0043165	0.0045366	0.004814635	1.57E-05
1999	0.0071384	0.0027815	0.0073877	0.004795	0.0046986	0.00388	0.0076424	0.0052395	0.0039528	0.0041219	0.004459198	1.321E-05
2000	0.0064849	0.0025743	0.00672	0.0043655	0.0042566	0.0035302	0.0069181	0.0047775	0.0035659	0.0036945	0.004123389	3.388E-07
2001	0.0058176	0.0023148	0.0063167	0.0039392	0.0038975	0.0033093	0.0066027	0.0045446	0.003347	0.0034517	0.003772359	1.132E-05
2002	0.0055508	0.0022535	0.0065259	0.0038238	0.0037476	0.0034338	0.0066909	0.0047387	0.0033719	0.0034247	0.003802569	1.121E-05
2003	0.0051405	0.0022273	0.0069381	0.0037121	0.003772	0.0035065	0.006862	0.0049655	0.003441	0.0035268	0.003877941	1.045E-05
2004	0.004743	0.0021185	0.0068267	0.0035285	0.0036958	0.0034206	0.0067454	0.0049385	0.0033858	0.0034637	0.003822432	9.057E-06
2005	0.004192	0.001855	0.006265	0.0031698	0.0033602	0.003253	0.0061567	0.004569	0.0032628	0.0033011	0.003607973	8.428E-06
2006	0.0036933	0.0016608	0.0055872	0.0028462	0.0030266	0.0029444	0.005552	0.0041103	0.0029722	0.0029862	0.00324056	6.592E-06
2007	0.0030957	0.0013274	0.0045484	0.0024706	0.0025369	0.0025463	0.0045529	0.0036394	0.0026364	0.0026463	0.002676143	0.0001671
2008	0.0025267	0.0010878	0.0038639	0.0020546	0.0021327	0.0021359	0.0038122	0.0030854	0.0022588	0.0022677	0.002237262	0.0001454
2009	0.0023697	0.0010632	0.0036865	0.0019717	0.0020851	0.002112	0.0037008	0.0030495	0.0022616	0.0022505	0.002186046	0.0001348
2010	0.0020784	0.0009619	0.0032957	0.001767	0.0018775	0.0019336	0.0033319	0.0027821	0.0020225	0.0020221	0.001980465	0.0001192
2011	0.0017069	0.0007927	0.0027088	0.0014577	0.0015493	0.0016014	0.0027419	0.0022887	0.0016635	0.0016639	0.001634851	9.963E-05

China [kg CO_{2-eq}/$]	Electricity, Gas and Water	Construction	Maintenance and Repair	Wholesale Trade	Retail Trade	Hotels and Restraurants	Transport	Post and Telecommunications	Finacial Intermediation and Business Activities	Public Admin	Education, Health and Other Services	Private Households	Others
1992	0.0508137	0.008696766	0.0052446	0.0052445	0.0052446	0.008324097	0.0077659	0.0053386	0.0041899	0.0049602	0.0093114	0.002194936	0.0049602
1993	0.0368405	0.007950548	0.0034744	0.0034745	0.0034744	0.006138379	0.0066832	0.0039834	0.0025434	0.0044379	0.0072689	0.002585291	0.0044379
1994	0.0445019	0.009088626	0.0039704	0.0039704	0.0039704	0.006994609	0.0070971	0.0045303	0.0029189	0.004856	0.008249	0.003007847	0.0048559
1995	0.0342783	0.007537936	0.0032445	0.0032446	0.0032445	0.005788603	0.0058532	0.0037151	0.0023851	0.003928	0.0067284	0.002538325	0.003928
1996	0.0279842	0.006243145	0.0028238	0.0028238	0.0028237	0.005041226	0.0048837	0.0033747	0.0021179	0.0034797	0.0058788	0.002021692	0.0034798
1997	0.0281958	0.005953429	0.0027247	0.0027246	0.0027246	0.004758169	0.0048854	0.0029527	0.0020605	0.0031875	0.0054055	0.002160939	0.0031875
1998	0.0194428	0.005234406	0.0025029	0.0025029	0.0025029	0.003722308	0.0044925	0.0018757	0.0019739	0.0027698	0.0049336	0.003572335	0.0027698
1999	0.0192552	0.004879978	0.002368	0.002368	0.002368	0.003514313	0.0043842	0.0017666	0.0018523	0.002625	0.004727	0.003374221	0.002625
2000	0.0175351	0.004444353	0.0022124	0.0022124	0.0022124	0.003287596	0.0042464	0.0016053	0.001706	0.0024493	0.004368	0.003117932	0.0024493
2001	0.017948	0.00412402	0.0019884	0.0019885	0.0019885	0.002923799	0.0038479	0.0015102	0.0015555	0.0022226	0.0040517	0.002841572	0.0022226
2002	0.0199452	0.004146819	0.002031	0.0020311	0.002031	0.002890757	0.0038488	0.001581	0.0016488	0.0022325	0.0040073	0.002850465	0.0022325
2003	0.021784	0.004210997	0.00204	0.00204	0.00204	0.002863364	0.003914	0.0016252	0.0016573	0.002229	0.0039156	0.002852914	0.002229
2004	0.0224996	0.004118785	0.0019568	0.0019568	0.0019568	0.002733709	0.003764	0.0015796	0.001587	0.0021053	0.0036644	0.002740645	0.0021053
2005	0.018345	0.003730621	0.0015572	0.0015572	0.0015572	0.002477906	0.00361	0.0017721	0.0016643	0.0019727	0.0034079	0.002421484	0.0019727
2006	0.0163641	0.003349518	0.0014085	0.0014085	0.0014085	0.002224408	0.0032477	0.0015873	0.0014666	0.001728	0.002985	0.002178621	0.001728
2007	0.0128341	0.002853381	0.0011366	0.0011366	0.0011366	0.001963525	0.0027457	0.0011582	0.0011643	0.0012231	0.0026549	0.001873104	0.0012231
2008	0.0104899	0.002412122	0.0009434	0.0009434	0.0009434	0.001620372	0.0022369	0.0009673	0.0009764	0.0010167	0.002188	0.001568897	0.0010167
2009	0.0104956	0.00238123	0.0009367	0.0009368	0.0009368	0.001572142	0.0021564	0.0009869	0.0009663	0.0010213	0.0021243	0.001550239	0.0010213
2010	0.0103582	0.002141988	0.0008597	0.0008597	0.0008597	0.001431788	0.0019241	0.0009118	0.000878	0.0009244	0.0019099	0.001404032	0.0009244
2011	0.0085269	0.001762192	0.0007091	0.0007091	0.0007091	0.001181127	0.0015842	0.0007491	0.0007221	0.0007551	0.0015701	0.001157886	0.0007551

Appendix D. Carbon emissions intensities of the BRICS metal industries [kilogramCO_{2-eq}/$]



References

Abbasi, M., & Nilsson, F. (2012). Themes and challenges in making supply chains environmentally sustainable. *Supply Chain Management: An International Journal, 17*(5), 517–530.

Acquaye, A. A., & Duffy, A. P. (2010). Input–output analysis of Irish construction sector greenhouse gas emissions. *Building and Environment, 45*(3), 784–791.

Acquaye, A., Feng, K., Oppon, E., Salhi, S., Ibn-Mohammed, T., Genovese, A., et al. (2017). Measuring the environmental sustainability performance of global supply chains: A multi-regional input-output analysis for carbon, sulphur oxide and water footprints. *Journal of Environmental Management, 187*, 571–585.

Acquaye, A., Genovese, A., Barrett, J., & Koh, L. (2014). Benchmarking carbon emissions performance in supply chains. *Supply Chain Management: An International Journal, 19*(3), 306–321.

Afful-Dadzie, A., Afful-Dadzie, E., & Turkson, C. (2016). A TOPSIS extension framework for re-conceptualizing sustainability measurement. *Kybernetes, 45*(1), 70–86.

Afionis, S., Sakai, M., Scott, K., Barrett, J., & Gouldson, A. (2017). Consumption-based carbon accounting: Does it have a future? *Wiley Interdisciplinary Reviews: Climate Change, 8*(1), 1–19.

Ahi, P., & Searcy, C. (2015). Assessing sustainability in the supply chain: A triple bottom line approach. *Applied Mathematical Modelling, 39*(10), 2882–2896.

Akashi, O., Hanaoka, T., Matsuoka, Y., & Kainuma, M. (2011). "A projection for global CO2 emissions from the industrial sector through 2030 based on activity level and technology changes. *Energy, 36*, 1855–1867.

Alcott, B. (2012). Population matters in ecological economics. *Ecological Economics, 80*, 109–120.

Allwood, J. M., Ashby, M. F., Gutowski, T. G., & Worrell, E. (2011). Material efficiency: A white paper. *Resources, Conservation and Recycling, 55*(3), 362–381.

Allwood, J. M., Cullen, J. M., & Milford, R. L. (2010). "Options for achieving a 50% cut in industrial carbon emissions by 2050. *Environmental Science and Technology, 44*(6), 1888–1894.

Arens, M., Worrell, E., & Schleich, J. (2012). Energy intensity development of the German iron and steel industry between 1991 and 2007. *Energy, 45*(1), 786–797.

Azapagic, A., & Perdan, S. (2000). Indicators of sustainable development for industry: A general framework. *Process Safety and Environmental Protection, 78*(4), 243–261.

Barrett, J., Peters, G., Wiedmann, T., Scott, K., Lenzen, M., Roelich, K., & Le Quéré, C. (2013). Consumption-based GHG emission accounting: A UK case study. *Climate Policy, 13*(4), 451–470.

Bazan, E., Jaber, M. Y., & Zanoni, S. (2015). Supply chain models with greenhouse gases emissions, energy usage and different coordination decisions. *Applied Mathematical Modelling, 39*(17), 5131–5151.

Beske, P., & Seuring, S. (2014). Putting sustainability into supply chain management. *Supply Chain Management: An International Journal, 19*(3), 322–331.

Bhagwati, J., & Panagariya, A. (1996). The theory of preferential trade agreements: Historical evolution and current trends. *The American Economic Review, 86*(2), 82–87.

Bosetti, V., Carraro, C., & Tavoni, M. (2009). Climate change mitigation strategies in fast-growing countries: The benefits of early action. *Energy Economics, 31*, S144–S151.

BRICS6.. Sixth BRICS Summit – Fortaleza Declaration. (2014). http://brics6.itamaraty.gov.br/media2/press-releases/214-sixth-brics-summit-fortaleza-declaration (Accessed 15 April 2015).

Cerri, C. C., Maia, S. M. F., Galdos, M. V., Cerri, C. E. P., Feigl, B. J., & Bernoux, M. (2009). Brazilian greenhouse gas emissions: The importance of agriculture and livestock. *Scientia Agricola, 66*(6), 831–843.

Chakraborty, D., & Mukhopadhyay, K. (2014). "The methodology, *Water pollution and abatement policy in India: 10* (pp. 47–51). Netherlands: Springer.

Court, C. D., Munday, M., Roberts, A., & Turner, K. (2015). Can hazardous waste supply chain 'hotspots' be identified using an input–output framework. *European Journal of Operational Research, 241*(1), 177–187.

Daly, H. E., & Farley, J. (2011). *Ecological economics: Principles and applications*. Washington: Island Press.

Devika, K., Jafarian, A., & Nourbakhsh, V. (2014). Designing a sustainable closed-loop supply chain network based on triple bottom line approach: A comparison of metaheuristics hybridization techniques. *European Journal of Operational Research, 235*(3), 594–615.

Dey, A., Laguardia, P., & Srinivasan, M. (2011). Building sustainability in logistics operations: A research agenda. *Management Research Review, 34*(11), 1237–1259.

Ding, H., Liu, Q., & Zheng, L. (2016). Assessing the economic performance of an environmental sustainable supply chain in reducing environmental externalities. *European Journal of Operational Research, 255*(2), 463–480.

EAPSA. South African Government's position on climate change. (2013). http://www.climateaction.org.za/cop17-cmp7/sa-government-position-on-climate-change (Accessed 8th April 2015)

Ebiefung, A., & Kostreva, M. (1993). The generalized Leontief input–output model and its application to the choice of new technology. *Annals of Operations Research, 44*(2), 161–172.

Epstein, D. (2014). "New development? The BRICS Bank and the International System. *Harvard International Review, 36*(2), 12.

Ewing, B. R., Hawkins, T. R., Wiedmann, T. O., Galli, A., Ercin, A. E., Weinzettel, J., et al. (2012). Integrating ecological and water footprint accounting in a multi-regional input–output framework. *Ecological Indicators, 23*, 1–8.

Fawcett, S. E., & Magnan, G. M. (2002). The rhetoric and reality of supply chain integration. *International Journal of Physical Distribution & Logistics Management, 32*(5), 339–361.

Fischedick, M., Roy, J., Abdel-Aziz, A., Acquaye, A., Allwood, J. M., Ceron, J.-P., et al. (2014). Industry. *Climate change 2014: Mitigation of climate change. contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Fischer, C., & Newell, R. G. (2008). Environmental and technology policies for climate mitigation. *Journal of Environmental Economics and Management, 55*(2), 142–162.

Font, X., & Harris, C. (2004). Rethinking standards from green to sustainable. *Annals of Tourism Research, 31*(4), 986–1007.

Fourcade, M. (2013). The material and symbolic construction of the BRICs: Reflections inspired by the RIPE Special Issue. *Review of International Political Economy, 20*(2), 256–267.

Freeman, S. L., Niefer, M. J., & Roop, J. M. (1997). Measuring industrial energy intensity: Practical issues and problems. *Energy Policy, 25*(7), 703–714.

Ganesh, M., Raghunathan, S., & Rajendran, C. (2014). The value of information sharing in a multi-product, multi-level supply chain: Impact of product substitution, demand correlation, and partial information sharing. *Decision Support Systems, 58*, 79–94.

Genovese, A., Morris, J., Piccolo, C., & Koh, S. L. (2017). Assessing redundancies in environmental performance measures for supply chains. *Journal of Cleaner Production* 10.1016/j.jclepro.2017.05.186.

Gereffi, G., Humphrey, J., & Sturgeon, T. (2005). The governance of global value chains. *Review of International Political Economy, 12*(1), 78–104.

Gonzalez, E. D. R. S., Sarkis, J., Huisingh, D., Huatuco, L. H., Maculan, N., Montoya-Torres, J. R., et al. (2015). Making real progress toward more sustainable societies using decision support models and tools: Introduction to the special volume. *Journal of Cleaner Production, 105*, 1–13.

Guardian. (2011). BRICS' emergence raises the environmental stakes. Guardian. http://www.theguardian.com/sustainable-business/brics-economies-emerging-markets-global-values, (Accessed 20th March 2015).

Guinée, J. B. (2002). Handbook on life cycle assessment operational guide to the ISO standards. *The International Journal of Life Cycle Assessment, 7*(5), 311–313.

Gunasekaran, A., Patel, C., & McGaughey, R. E. (2004). A framework for supply chain performance measurement. *International Journal of Production Economics, 87*(3), 333–347.

Gutowski, T. G., Sahni, S., Allwood, J. M., Ashby, M. F., & Worrell, E. (2013). "The energy required to produce materials: Constraints on energy-intensity improvements, parameters of demand. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 371*, 20120003.

Hart, S. L. (1995). A natural-resource-based view of the firm. *Academy of Management Review, 20*(4), 986–1014.

Hassini, E., Surti, C., & Searcy, C. (2012). A literature review and a case study of sustainable supply chains with a focus on metrics. *International Journal of Production Economics, 140*(1), 69–82.

Heltberg, R., Siegel, P. B., & Jorgensen, S. L. (2009). Addressing human vulnerability to climate change: Toward a 'no-regrets' approach. *Global Environmental Change, 19*(1), 89–99.

Holweg, M., Disney, S., Holmström, J., & Småros, J. (2005). Supply chain collaboration: Making sense of the strategy continuum. *European Management Journal, 23*(2), 170–181.

Horvath, L. (2001). Collaboration: The key to value creation in supply chain management. *Supply Chain Management: An International Journal, 6*(5), 205–207.

Hu, G., & Bidanda, B. (2009). Modeling sustainable product lifecycle decision support systems. *International Journal of Production Economics, 122*(1), 366–375.

Huang, Y. A., Weber, C. L., & Matthews, H. S. (2009). Categorization of scope 3 emissions for streamlined enterprise carbon footprinting. *Environmental Science & Technology, 43*(22), 8509–8515.

Hubacek, K., Feng, K., & Chen, B. (2011). Changing lifestyles towards a low carbon economy: An IPAT analysis for China. *Energies, 5*(1), 22–31.

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2014). Integrating economic considerations with operational and embodied emissions into a decision support system for the optimal ranking of building retrofit options. *Building and Environment, 72*, 82–101.

Ibn-Mohammed, T., Koh, S. C. L., Reaney, I. M., Acquaye, A., Schileo, G., Mustapha, K. B., et al. (2017). Perovskite solar cells: An integrated hybrid lifecycle assessment and review in comparison with other photovoltaic technologies. *Renewable and Sustainable Energy Reviews, 80*, 1321–1344.

Intergovernmental Panel on Climate Change, IPCC.. Section 7.6.3: Costing methodologies: Top–down and bottom–up models. (2001). http://www.ipcc.ch/ipccreports/tar/wg3/index.php?idp=310 (Accessed 15 March 2015).

International Standard Organisation, ISO. (1998). *ISO 14041: Environmental management – Lifecycle assessment – Goal and scope definition and Inventory analysis*. ISO. Geneva.

IPCC. (2014). Summary for policymakers. *Climate change 2014, mitigation of climate change. contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Jaehn, F. (2016). Sustainable operations. *European Journal of Operational Research, 253*(2), 243–264.

Jakob, M., Steckel, J. C., & Edenhofer, O. (2014). Consumption-versus production-based emission policies. *Annual Review of Resource Economics, 6*(1), 297–318.

Kagawa, S., Suh, S., Hubacek, K., Wiedmann, T., Nansai, K., & Minx, J. (2015). CO_2 emission clusters within global supply chain networks: Implications for climate change mitigation. *Global Environmental Change*. doi:10.1016/j.gloenvcha.2015.04.003.

Khanna, P. (2014). New BRICS bank a building block of alternative world order. *New Perspectives Quarterly, 31*(4), 46–48.

Kucukvar, M., Egilmez, G., & Tatari, O. (2014). "Sustainability assessment of US final consumption and investments: Triple-bottom-line input–output analysis. *Journal of Cleaner Production, 81*, 234–243.

Koh, S. L., Genovese, A., Acquaye, A. A., Barratt, P., Rana, N., Kuylenstierna, J., et al. (2013). Decarbonising product supply chains: design and development of an integrated evidence-based decision support systemthe supply chain environmental analysis tool (SCEnAT). *International Journal of Production Research, 51*(7), 2092–2109.

Koh, S. C. L., Ibn-Mohammed, T., Acquaye, A., Feng, K., Reaney, I. M., Hubacek, K., Fujii, H., & Khatab, K. (2016). Drivers of US toxicological footprints trajectory 1998–2013. *Scientific Reports, 6*, 39514.

Lai, K.-H., & Wong, C. W. Y. (2012). Green logistics management and performance: Some empirical evidence from Chinese manufacturing exporters. *Omega, 40*(3), 267–282.

Larsen, H. N., & Hertwich, E. G. (2009). The case for consumption-based accounting of greenhouse gas emissions to promote local climate action. *Environmental Science & Policy, 12*(7), 791–798.

Lambert, D. M., & Cooper, M. C. (2000). Issues in supply chain management. *Industrial Marketing Management, 29*(1), 65–83.

Leal-Arcas, R. (2013). The BRICS and climate change, *International affairs forum: 4* (pp. 22–26). Taylor & Francis.

Lehtinen, J., & Ahola, T. (2010). Is performance measurement suitable for an extended enterprise? *International Journal of Operations & Production Management, 30*(2), 181–204.

Lenzen, M., Moran, D., Kanemoto, K., & Geschke, A. (2013). Building Eora: A global multi-region input–output database at high country and sector resolution. *Economic Systems Research, 25*(1), 20–49.

Leontief, W. (1936). Quantitative input and output relations in the economic systems of the United States. *The Review of Economic Statistics, 18*(3), 105–125.

Mahlberg, B., & Luptacik, M. (2014). Eco-efficiency and eco-productivity change over time in a multisectoral economic system. *European Journal of Operational Research, 234*(3), 885–897.

Majeau-Bettez, G., Strømman, A. H., & Hertwich, E. G. (2011). Evaluation of process-and input–output-based life cycle inventory data with regard to truncation and aggregation issues. *Environmental Science & Technology, 45*(23), 10170–10177.

Marchi, V. D., Maria, E. D., & Micelli, S. (2013). "Environmental strategies, upgrading and competitive advantage in global value chains. *Business Strategy and the Environment, 22*(1), 62–72.

Mathews, J. A., & Tan, H. (2016). "Circular Economy: Lessons from China. *Nature, 531*, 440–442.

McDonough, W., & Braungart, M. (2002). *Cradle to cradle: Remaking the way we make things*. New York, NY: North Point Press.

Miller, R. E., & Blair, P. D. (2009). *Input-output analysis: Foundations and extensions*. Cambridge: Cambridge University Press.

Min, S., Roath, A. S., Daugherty, P. J., Genchev, S. E., Chen, H., Arndt, A. D., et al. (2005). Supply chain collaboration: What's happening? *The International Journal of Logistics Management, 16*(2), 237–256.

Muller, E., Hilty, L. M., Widmer, R., Schluep, M., & Faulstich, M. (2014). "Modeling metal stocks and flows: A review of dynamic material flow analysis methods. Environmental Science & Technology", 48(4), pp. 2102–2113.

Napp, T., Gambhir, A., Hills, T., Florin, N., & Fennell, P. (2014). "A review of the technologies, economics and policy instruments for decarbonising energy-intensive manufacturing industries. *Renewable and Sustainable Energy Reviews, 30*, 616–640.

Nayyar, D. (2016). "BRICS, developing countries and global governance. *Third World Quarterly, 37*(4), 575–591.

Neilson, J., Pritchard, B., & Yeung, H. W. C. (2014). "Global value chains and global production networks in the changing international political economy: An introduction. *Review of International Political Economy, 21*(1), 1–8.

O'Mahony, M., & Timmer, M. P. (2009). Output, input and productivity measures at the industry level: The EU KLEMS database. *The Economic Journal, 119*(538), F374–F403.

Paroussos, L., Fragkos, P., Capros, P., & Fragkiadakis, K. (2015). Assessment of carbon leakage through the industry channel: The EU perspective. *Technological Forecasting and Social Change, 90*, 204–219.

Peters, G. P. (2010). Carbon footprints and embodied carbon at multiple scales. *Current Opinion in Environmental Sustainability, 2*(4), 245–250.

Porter, M. (1985). *Competitive advantage: Creating and sustaining superior performance*. New York, NY: Free Press.

Prell, C., Feng, K., Sun, L., Geores, M., & Hubacek, K. (2014). The economic gains and environmental losses of US consumption: A world-systems and input–output approach. *Social Forces, 93*(1), 405–428.

Roy, R. (2000). Sustainable product-service systems. *Futures, 32*(3–4), 289–299.

Schaltegger, S., Lüdeke-Freund, F., & Hansen, E. G. (2012). "Business cases for sustainability: The role of business model innovation for corporate sustainability. *International Journal of Innovation and Sustainable Development, 6*(2), 95–119.

Serrenho, A. C., Mourão, Z. S., Norman, J., Cullen, J. M., & Allwood, J. M. (2016). "The influence of UK emissions reduction targets on the emissions of the global steel industry. *Resources, Conservation and Recycling, 107*, 174–184.

Shaw, N.. BRIC by BRIC: How our emerging markets are tackling carbon emissions?. (2013). http://www.sustainablebusinesstoolkit.com/bric-countries-carbon-emissions/ (Accessed 20th March 2015).

Sundarakani, B., De Souza, R., Goh, M., Wagner, S. M., & Manikandan, S. (2010). Modeling carbon footprints across the supply chain. *International Journal of Production Economics, 128*(1), 43–50.

Taticchi, P., Garengo, P., Nudurupati, S. S., Tonelli, F., & Pasqualino, R. (2015). A review of decision-support tools and performance measurement and sustainable supply chain management. *International Journal of Production Research, 53*(21), 6473–6494.

Takahashi, K., Nansai, K., Tohno, S., Nishizawa, M., Kurokawa, J.-I., & Ohara, T. (2014). Production-based emissions, consumption-based emissions and consumption-based health impacts of PM2.5 carbonaceous aerosols in Asia. *Atmospheric Environment, 97*, 406–415.

Timmer, M. P., Erumban, A. A., Los, B., Stehrer, R., & de Vries, G. J. (2014). "Slicing up global value chains. *The Journal of Economic Perspectives, 28*(2), 99–118.

Tukker, A., & Dietzenbacher, E. (2013). Global multiregional input–output frameworks: An introduction and outlook. *Economic Systems Research, 25*(1), 1–19.

UNEP and SETAC. (2011). *Global guidance principles for life cycle assessment databases: A basis for greener processes and products*. Italy: United Nations Environment ProgrammeMilan, Accessed: 20 January 2015, Available at: http://www.lifecycleinitiative.org/wp-content/uploads/2012/12/2011%20-%20Global%20Guidance%20Principles.pdf.

US Energy Information Administration.. Country analysis: Brazil. (2013). http://www.eia.gov/beta/international/country.cfm?iso=BRA (Accessed 10 March 2015).

Varsei, M., Soosay, C., Fahimnia, B., & Sarkis, J. (2014). Framing sustainability performance of supply chains with multidimensional indicators. *Supply Chain Management: An International Journal, 19*(3), 242–257.

Ward, H., Burger, M., Chang, Y. J., Fürstmann, P., Neugebauer, S., Radebach, A., et al. (2017). Assessing carbon dioxide emission reduction potentials of improved manufacturing processes using multiregional input output frameworks. *Journal of Cleaner Production, 163*, 154–165.

Washington Post.. Xi confident in BRICS future. (2014). http://chinawatch.washingtonpost.com/2014/07/xi_confident_in_brics_future/ (Accessed: 20th March 2015).

West, G. R., & Jackson, R. W. (2015). Simulating impacts on regional economies: A modelling alternative. In I. R. M. (Association (Ed.), *Hospitality travel and tourism: Concepts, methodologies, tools and applications*. Pennsylvania: IGI Global.

World Bank. (2015). *World bank open data*. Washington, USA *http://data.worldbank.org/* (Accessed 2nd May 2015).

World Bank. (2016). *World bank open data: Russian federation*. Washington, USA *http://data.worldbank.org/country/russian-federation?view=chart* (accessed: 1 March 2017).

Wu, L., Liu, S., Liu, D., Fang, Z., & Xu, H. (2015). Modelling and forecasting CO_2 emissions in the BRICS (Brazil, Russia, India, China, and South Africa) countries using a novel multi-variable grey model. *Energy, 79*, 489–495.

Wu, X., & Zhang, Z. (2005). Input–output analysis of the Chinese construction sector. *Construction Management and Economics, 23*(9), 905–912.

Xu, Y., & Dietzenbacher, E. (2014). A structural decomposition analysis of the emissions embodied in trade. *Ecological Economics, 101*, 10–20.

Yang, Q., & Song, B. (2006). Eco-design for product lifecycle sustainability. In *Proceedings of the IEEE international conference on industrial informatics* (pp. 548–553).

Yuan, Z., Bi, J., & Moriguichi, Y. (2006). The circular economy: A new development strategy in China. *Journal of Industrial Ecology, 10*(1-2), 4–8.

Zhu, J. (2014). *Quantitative models for performance evaluation and benchmarking: Data envelopment analysis with spreadsheets*: 213. Springer.

Zhu, Q., Sarkis, J., & Lai, K.-h. (2008). Confirmation of a measurement model for green supply chain management practices implementation. *International Journal of Production Economics, 111*(2), 261–273.