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The Global Footprint of Sectors

by

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Abstract

Studies investigating the footprint of nations have reported significant carbon-leakage between countries and the need to track emissions responsibility under a consumption-based accounting to complement traditional production estimates. Nonetheless, these works have largely ignored the impact of consumption by sectors in generating greenhouse gas emissions, which remained estimated under a production-based system. This, on its turn, only reveals the direct emissions released by a sector, which may be producing goods that are inputs to other sectors, thus allowing some industries to conceal part of their emissions. Therefore, the primary purpose of this study is to determine the footprint of sectors by taking stock of the pollution embedded in its input requirements in upstream paths in the value chain. The empirical part of this research used a Global Multi-Regional Input-Output table obtained from Exiobase 3. It includes 44 countries, 5 rest of the world regions and 200 sectors. The results provide a new contribution by estimating, for the first time, the footprint of highly detailed sectors at the global level. The findings introduce a different pattern of sectorial responsibility for emissions.

Key words: Input-Output analysis; Sectors; Footprint; Consumption-based accounting.

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1 Introduction

A consumption-based accounting (CBA) of emissions (also known as emissions footprint) was introduced to complement traditional methods of pollution estimates based on production, such as those in which countries have to submit to the United Nations Framework Convention on Climate Change (UNFCCC). The growth in globalization, and the increasing geospatial divide between the point of production and consumption, has generated a considerable body of research aimed at investigating pollution embodied in international trade, and whether emissions are displaced from developed to developing countries (Wiedmann & Lenzen, 2018). The need for a consumption method has rested on arguments that the parties who benefit from a process should bear some of the responsibility for its associated byproducts (Davis & Caldeira, 2010), as well as on its ability to addresses carbon leakage, that is, a reduction in emissions in developed countries that is partially due to a shift in consumption patterns towards carbon intensive imports of outsourced industries (Tukker, Pollitt & Henkemans, 2020). CBA estimates have shown an increased responsibility of highly developed nations in demanding production to take place, and a significant displacement of pollution through international trade (e.g., Peters et al., 2011; Caldeira & Davis, 2011). For these reasons, a consumption accounting has been argued to provide high relevance for emissions mitigation policies and a fairer assessment of pollution responsibility (Caldeira & Davis, 2011; Peters et al., 2011).

Nevertheless, CBA has largely ignored the role of sectors in generating greenhouse gas (GHG) emissions, which remained estimated primarily on a production-based accounting (PBA), that is, sectors are only responsible for the emissions that they directly emit. Yet, the delivery of goods or services by a sector is anchored into inputs for its production, which are delivered by other sectors (Parrique et al., 2019; Suh, 2006; Tarancón Morán & del Río González, 2007). These latter sectors also require inputs for production, which are subsequently delivered by a different set of sectors, creating complex supply-chain interlinkages (O’Rourke, 2014). A PBA will reveal the total pollution taking place directly within a sector, including the emissions generated to produce inputs for other sectors, but not the emissions that occurred during the production of its own input requirements. This can allow some industries to conceal a share of their emissions (Long et al., 2018). This concealing has been termed a ‘cross-sector carbon leakage' (Long et al., 2018), which might undermine policies to set mitigation priorities, since it hides the sectors that demanded the pollution to occur (for input production), and as a consequence, it hides which activities will be most affected by emissions reduction strategies (Wood et al., 2020b; Long et al., 2018).

Recent concerns on policy instruments for addressing the consumption side of emissions has led studies to quantify the footprint of specific products or consumption categories (e.g., Moran et al., 2020) and investigate the design of policies for mitigation through a change on product demand or consumption taxes (e.g., Grubb et al., 2020; Pollitt, Neuhoff & Lin, 2020). This concern is reflected on the European Union's Carbon emission mitigation by Consumption-based Accounting and Policy project (EU Carbon-CAP), which aim to stimulate research and policy instruments to complement the European Union's production emissions mitigation targets. Nonetheless, these recent advances have largely focused on addressing selected goods directly available to households and the implications of a change in individual consumptive behavior. Although the largest share of emissions that are produced can ultimately be assigned to household consumption (apart from other final consumers, such as government expenditure), a significant share of this emissions is not responsive to individual demand side changes. Most individuals cannot choose the materials used in the construction of their apartments, or the source of electricity they consume, not to mention decisions over larger infrastructure projects. For instance, Moran et al. (2020) selects ten consumption categories (e.g., food, mobility, textiles) based on the fact that these are amenable to individual demand-side interventions. Therefore, and notwithstanding the importance the above studies may entail, the emissions embedded in the transactions between sectors that are beyond the realm of influence of individuals (or of policies that address goods available to households) are not addressed.

In this sense, this study aims to investigate the responsibility of sectors for GHG emissions at the global level based on a consumption accounting approach, and as such, to address cross-sector carbon leakage by accounting for all upstream emissions in the value-chain. Additionally, this work seeks to compare the footprint of sectors to their standard production-based estimates, and to uncover the sources of inputs causing sectors to exhibit high footprints. The calculations of sector footprints are done individually by country and taking account of their technological differences, thus in addition to aggregating the results at the global level, this study aims to provide a regional accountability for the sectors with the highest footprints. This, on its turn, may provide a different set of sectorial responsibility for anthropogenic emissions, and thus assist policy making to set emissions reduction priorities that take the interrelationship between sectors into account. In order to achieve this, a Global Multi-Regional Input-Output table, for the year 2017, obtained from Exiobase 3 was used. It contains a highly disaggregated sectorial resolution covering 200 sectors in 44 countries and 5 rest of the world (RoW) regions. Finally, in order to achieve its aims, this paper will address the following questions:

- *I. What were the greenhouse gas footprint of sectors at the global level, both in absolute terms and relative to their economic output in the year 2017?*
    - *a. In which regions did the most polluting sectors exhibit the highest per capita footprint?*

- *II. What were the underlying consumption activities causing a shift in the responsibility of the sectors with the highest footprints?*

1.1 Outline of the Thesis and Technical Notes

The remaining part of the paper proceeds as follows: chapter 2 discusses the main literature around input-output applications to environmental analysis as well as an overview of studies analyzing the environmental implications of the interrelationship of sectors. Chapters 3 and 4 describe the data and calculation procedures used in this study. Chapter 5 presents the results followed by chapter 6 which discusses its implications. Chapter 7 summaries the work and outlines limitations and future areas of research. Finally, all calculations were performed using Python programming language and Excel. A complete set of results and code syntax is available from the author upon request.

2 Theory

2.1 Previous Research

Input-output analysis began its application in the 1940s upon publishing of the first large-scale IO tables for the United States – where its use was largely concerned with employment and broader issues of development (Rose & Miernyk, 1989). Nonetheless, it was David Wright (1974, 1975) who first used an input-output analysis for environmental applications. Influenced by the oil shocks of the 1970s (see Wright, 1974), these initial works were concerned with the total required energy inputs (and its associated costs) for industrial and service production (Costanza, 1980; Bullard III & Herendeen, 1975; Wright, 1975, 1974). IO methods allowed for the estimation of the total consumption of energy across the supply chain of a product, and thus the term ‘embodied energy’ was introduced, meaning the direct and indirect energy burned and dissipated that is passed on to intermediate and final products (Costanza, 1980; Bullard III & Herendeen, 1975). The term has since been appropriated to refer to ‘embodied emissions’, as well as other forms of pollution, as IO studies began investigating the growing importance of anthropogenic climate change (Lenzen, 1998), and the role in which international trade affects carbon emissions (e.g., Peters et al., 2011; Peters & Hertwich, 2008a).

The environmental analysis of international trade has estimated the responsibility of national emissions based on the total consumption of countries (e.g., Caldeira & Davis, 2011; Davis & Caldeira, 2010; Hertwich & Peters, 2009). Countries are tasked with submitting their emissions inventory to the United Nations Framework Convention on Climate Change (UNFCCC), which accounts for pollution generated within territorial institutional units (Davis & Caldeira, 2010; Peters & Hertwich, 2008b). Nonetheless, arguments were laid out for the need of a consumption based approach (CBA) where individuals who consume and demand products should also bear some of the responsibility of its byproducts (Davis & Caldeira, 2010). As well as that a consumption method addresses carbon leakage, that is, a displacement of environmental impacts through international trade due to the increasing geographical distance between production and consumption (Peters & Hertwich, 2008b).

The results of these early studies converge on showing a significant transfer of emissions embodied in trade from developed to developing countries (Davis & Caldeira, 2010; Hertwich & Peters, 2009; Peters & Hertwich, 2008a), as well as a significant growth in the proportion of global carbon and greenhouse gas emissions attributable to international trade between the 1990s and the first decade of the 2000s (Caldeira & Davis, 2011; Peters et al., 2011). The increasing displacement of pollution was not limited to emissions, with other environmental pressures such as energy, material, land and water use all showing a growth in the share total impact displaced through trade (Hoekstra & Wiedmann, 2014; Wiedmann & Lenzen, 2018; Wood et al., 2018). Nevertheless, the national footprint estimation, as a better policy indicator, have also been criticized for not being responsive to a country's efforts in cleaning its export industries (Kander et al., 2015). Since exports are excluded from a consumption-based accounting, improvements in carbon intensity in such industries will be accredited to importing countries instead. As such, estimations adjusting for technological differences in exports have reported a lower magnitude of emissions transfer, and a more heterogeneous role between countries, as opposed to a common feature of transfer from developed to developing ones (Baumert et al., 2019; Kander et al., 2015).

Recent reviews, nonetheless, show that the global financial crisis in 2008 was an influential turning point in reducing emissions transfer (Karstensen, Peters & Andrew, 2018). Emissions transfer have declined in the post-crisis, and albeit experienced a rebound in 2010 and 2011, they declined again and plateaued until 2016 (Wood et al., 2020a, 2020b). Albeit a reduction in GDP and consumption of imports in the European Union (EU) is the single most important factor accounting for the reduction in footprint and emissions transfer in the EU (Karstensen, Peters & Andrew, 2018), Wood et al. (2020a) reports that a reduction of carbon intensity of products exported from non-OECD countries lies as the main contributor for emissions embodied in trade not returning to pre-crisis levels. Nonetheless, total absolute emission within the EU began rising again between 2014 and 2017, driven by higher rates of GDP growth (Karstensen, Peters & Andrew, 2018).

The recent stabilization of emissions embodied in trade led studies to focus on the consumption side of products, taking into account the entire supply chain of production, to quantify and deliver policies to reduce overall footprints (Grubb et al., 2020; Moran et al., 2020; Pollitt, Neuhoff & Lin, 2020). In spite of the importance this may entail – for instance, Moran et al. (2020) quantifies that adopting changes in consumer options, especially in transport, buildings and food products, can lower European carbon footprint by roughly 25% – these studies focus on a selection of products available directly to consumers and estimate the potential of emissions reduction from a behavioral change perspective, thus setting aside pollution that occurs beyond the scope of action and influence of households. The understanding of the responsibility of economic activities for global pollution requires the quantification of sectorial consumption, for which input-output and footprint studies have broadly disregarded.

Notable exceptions of this fact include the work of Long et al. (2018) who argues that emissions are concealed behind economic transactions between sectors, and that a sectorial footprint is required to address cross-sector carbon leakage. The authors, however, limit their analysis to emissions arising from energy generation in Japan, and estimate the footprint on a sectorial resolution of 14 activities, which introduces significant errors due to aggregation uncertainties (Tukker, Wood & Schmidt, 2020; Tukker et al., 2018). Perhaps the most comprehensive work taken to date comes from Wood et al. (2020b) who analyzes the emissions embodied in consumption in the European Union for 200 product groups. The footprint results coupled with production estimates allows for the estimation of activities demanding pollution to occur, as well as which sectors supplies the emissions (Wood et al., 2020b). Their results highlight the high impact of electricity generation, construction work and health service provision in the region under a footprint estimate (Wood et al., 2020b). A comprehensive global analysis with regional resolution is currently lacking in the literature.

2.2 Theoretical Approach

The Environmental Kuznets Curve (EKC) postulates the existence of an inverted-U-shaped curve when different forms of pollutants are plotted against per capita income levels (Kaika & Zervas, 2013; Dinda, 2004). The theory states that continued economic growth will eventually provide environmental betterment (Kaika & Zervas, 2013; Dinda, 2004). EKC was first laid out based on empirical observations where air quality deteriorates with per capita GDP growth at low levels of national income, but ameliorates once a certain threshold of income is surpassed (Grossman & Krueger, 1991, 1995). Panayotou (1993) introduced the term 'Environmental Kuznets Curve' to highlight that ecological degradation is expected to improve with the path of structural change that follows sustained economic growth, establishing a connection with the proposed evolution of inequality and income growth put forward years before by Simon

Kuznets (1955). The path of structural change of an economy from a low pollutive agrarian society towards emissions intensive manufacturing, to finally a clean service economy, was argued to be the main reason for the existence of an EKC (Panayotou, Peterson & Sachs, 2000; Panayotou, 1995). This has influenced climate strategies in the early 2000s, with studies proposing a transition towards a service economy as one of the main roadmaps to mitigate climate change (e.g., Pacala & Socolow, 2004).

Nonetheless, the existence of an EKC has been challenged on several grounds. For instance, a significant share of the observed reduction in pollution in upper income nations, measured in CO2 emissions, can be attributed to the outsourcing of carbon intensive production abroad to less developed regions (e.g., Caldeira & Davis, 2011; Davis & Caldeira, 2010; Hertwich & Peters, 2009; Peters et al., 2011). Statistical results of an EKC-like pattern were also deemed to have obtained spurious correlations, with reviews on the theory highlighting that "[…] most of the EKC literature is econometrically weak" (Stern, 2004, p.1420). In addition, a transition to a service economy has been argued to be the result of an illusion in terms of real production (Henriques & Kander, 2010; Kander, 2005). The growth of the service sector as a share of a nation's economy is partly a price response to productivity gains in manufacturing, whereas the expansion of the former should not expect to substitute production in the latter, thus, pollution reductions domestically (at least energy related pollution) are mainly the result of improvements in energy intensity (Henriques & Kander, 2010; Kander, 2005).

An ecological improvement through a service transition overlooks the fact that sectors are highly intertwined through complex webs of supply chain transactions (O'Rourke, 2014; Tarancón Morán & del Río González, 2007). Larsen and Hertwich (2009) have shown that approximately 93% of greenhouse gas emissions in municipal services in the city of Trondheim are indirect pollution arising from upstream paths. Comparably, Suh (2006) estimates that household consumption of service activities in the United States is responsible for roughly 40% of industrial GHG emissions, if inputs requirements to services are accounted for. In this sense, a service transition may be expected to not only *not* substitute production in other sectors, but its expansion to increase the demand for its input requirements, thus likely increasing production across the economic structure (Parrique et al., 2019; Suh, 2006).

3 Data

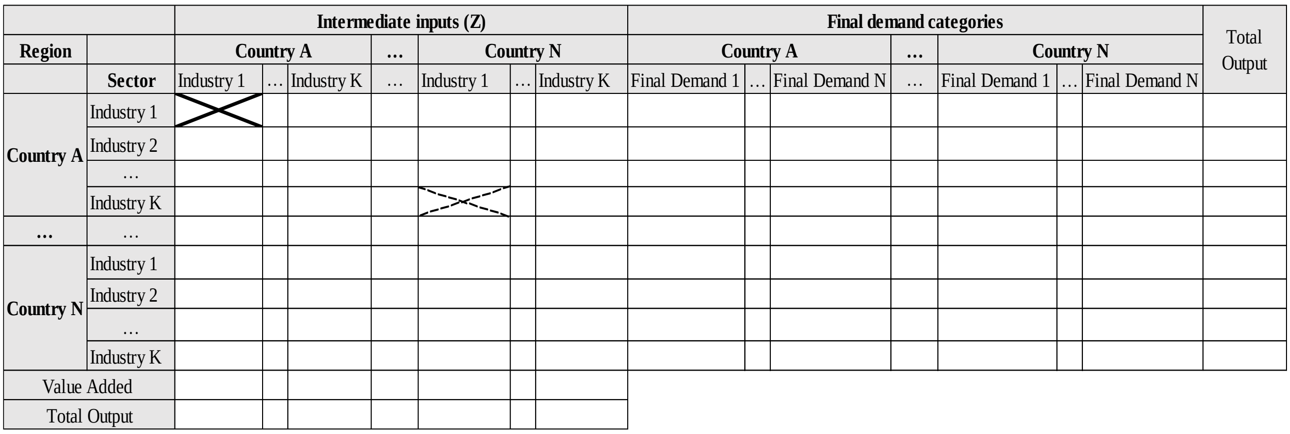
This work employs a Global Multi-Regional Input-Output (GMRIO) table from Exiobase 3 (Stadler et al., 2018). It makes use of the most recently available version of the dataset (i.e., version 3.8.1), which includes 44 countries and 5 aggregated rest of the world regions (RoW) in a sectorial resolution of 200 products (Stadler et al., 2021) – Appendix A provides a list of the countries covered. Since the purpose of this work is to obtain the responsibility of sectors based on a consumption accounting, Exiobase 3 was chosen since it provides one of the most detailed sector resolutions of all GMRIO databases. Other sources include, for instance, the World Input-Output Database (WIOD), which in its latest release allocates data for 56 sectors (Timmer et al., 2016) and Eora26, with 26 sectors (Lenzen et al., 2013). However, a low sectoral resolution increases uncertainties of the estimations (Tukker, Wood & Schmidt, 2020). For instance, agriculture, forestry and fishing is considered one sector in WIOD, thus not only the impacts of fishing and forestry cannot be decoupled from agriculture, as the analysis of which activities within agriculture are causing large impacts would have to remain speculative rather than empirical. A higher sector resolution allows the identification of the driving forces of emissions, which lies at the core analysis of this work.

Furthermore, Exiobase 3 provides one of the most recent data sources of GMRIO tables. GHGs are available by sector until 2017 (the year for which this study relies), whereas in WIOD the end year is 2009 (Timmer et al., 2015), with only CO2 updates until 2014 (Timmer et al., 2016) and Eora is 2015 for all GHGs (Lenzen et al., 2013). Therefore, the emissions data was also obtained from Exiobase 3 and include all major greenhouse gases, thus, carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), sulfur hexafluoride (SF6), hydrofluorocarbon (HFCs) and perfluorinated compounds (PFCs) are bundled together in a metric of CO2-equivalent (CO2-eq) and attributed to each sector (Stadler et al., 2018). CO2-eq is obtained by multiplying all other GHGs by their respective equivalent climate warming impact of CO2, known as their Global Warming Potentials (GWP), and subsequently aggregating the comparable metrics. GWP vary slightly over time, and this paper used the conversion metric in Exiobase 3 related to the GWP made public by the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013). Additionally, input-output tables provide emissions from the productive sectors of the economy, thus pollution from Land Use Change and Land Use Change and Forestry (LULUCF) which for instance, involves impacts from deforestation, are not included. Lastly, for country estimations, this paper has obtained population data from the World Bank (World Bank, 2021) for all countries except Taiwan, which was sourced from the Taiwanese National Development Council (National Development Council, 2021) and Eritrea, which was obtained from projections from the International Monetary Fund (IMF, 2020).

3.1 GMRIO Tables

Input-Output analyses are an *ex-post* investigation of supply-chain networks and are particularly valuable for footprint studies since they provide detailed transactions between countries and sectors, allowing for the estimation of indirect requirements throughout the value-chain production. Figure 3.1 below provides a general illustration of the structure of a Global Multi-Regional Input-Output table. The table is broadly split into a matrix of intermediate inputs (commonly known as the **Z** matrix) and a matrix of final demand categories (known as the **F** matrix). The former depicts the direct transactions between countries and industries, where the rows represent the production output, and the columns, the consumption of inputs. Thus, for instance, the filled X in Figure 3.1 represent the production of industry 1 in country A that is delivered to the same industry, also in country A. Similarly, the dotted X is what industry K in country A directly exports to industry 1 in country N. The matrix **F**, on its turn, outlines the demand requirements of non-industrial sectors, and it includes for instance household consumption and government expenditure.

Figure 3.1 Illustrative structure of a GMRIO table



		Intermediate inputs (Z)							**Final demand categories**							Total Output
Region		**Country A**			**…**	**Country N**			**Country A**			**…**	**Country N**			
	Sector	Industry 1	…	Industry K	…	Industry 1	…	Industry K	Final Demand 1	…	Final Demand N	…	Final Demand 1	…	Final Demand N	
Country A	Industry 1	×														
	Industry 2															
	…															
	Industry K					×										
…	…															
Country N	Industry 1															
	Industry 2															
	…															
	Industry K															
Value Added																
Total Output																

Source: own construction based on Timmer et al. (2015) and Wiedmann et al. (2006)

Exiobase 3 provides a GMRIO with 200 sectors (K = 200) and 49 regions (N = 49) resulting in a **Z** matrix of dimensions 9,800 x 9,800. Each country has 7 final demand categories consuming form each sector, thus a **F** matrix of dimensions 9,800 x 7 per country (or 9,800 x 343 in total). The construction of GMRIO in Exiobase 3 takes technological differences between producing countries into account (Stadler et al., 2018). Upon the estimation of a sector's footprint, the emissions responsibility will therefore include the technology-based emissions of imports the sector consumes. For instance, industry 1 in country N, in Figure 3.1, will include pollution it consumed domestically, with country N's technology, as well as pollution it imported, among others, from industry K with country A's technology.

4 Methods

4.1 The Birth of Input-Output Analysis

Input-Output analysis was conceived by Wassily Leontief in the early 1930s to provide empirical ground to investigations of the interdependence of various parts of the economic system (Leontief, 1936). It describes the economic transactions in a given year on a two-way table, where each row records the monetary outputs of goods and services, and each column register its equivalent absorption by a particular sector (Leontief, 1936). Other forms of inputs, not necessarily expressed in monetary terms, such as employment, can also be factored into the tables – since a given amount of labor was used in the production of outputs. Similarly, in the 1970s, Wassily himself has highlighted the suitability of input-output tables to incorporate different forms of economic externalities, prominently environmental impacts that follow a given level of technological system (Leontief, 1970).

4.2 Input-Output Calculations to Sectors

This section outlines the calculation procedures taken to obtain the GHG emissions footprint of sectors, as well as their production-based estimates by country. The process of obtaining environmental impacts of a sector’s total consumption was previously done within the ecological footprint literature. Prominently, Wiedmann et al. (2006) were the first to propose that the estimation of ecological footprints should take into account the consumptive behavior of sectors in order to ”depict the mutual interrelationships of economic activities and to assign indirect environmental burden arising from inter-industrial dependencies” (Wiedmann et al., 2006, p.29). The authors then applied their estimations of land pressure to the United Kingdom. The calculation procedures can be performed in four steps:

1. Obtain the direct and indirect requirement matrix.

2. Calculate emissions multiplier matrix.
3. Diagonalize final demand categories.
4. Obtain sectorial emissions in both consumption and production-based by country.

1. *Obtain the direct and indirect requirement matrix.*

An increase in production in one sector will raise the demand for its input requirements, which will cause an increase in production in other sectors. This is known as a first order requirement, i.e., the changes in one industry occurring directly due to changes in another industry. Nonetheless, as soon as a sector changes its output as a response, it will too change its input demand, which will trigger in itself changes across the value-chain of production. This cascading effect represent the indirect changes occurred due to an initial increase in production. The direct and indirect requirement matrix, known as the Leontief inverse (**L**), captures this supply-chain effect and it is obtained through estimating standard input-output calculations. Let **A** represent the technical coefficient matrix, which is obtained by dividing each transaction between industries in the intermediate delivery matrix **Z** by their respective industry's total output.

$$A = \left[a_{ij}\right] = \left[\frac{z_{ij}}{x_i}\right] \tag{1}$$

Matrix **A** in this work has dimensions 9,800 x 9,800 and each of its elements a_{ij} represent the amount – in monetary value – delivered by industry i to produce one euro unit of good in industry j. The technical coefficient matrix **A** captures the first order requirements, and one can obtain the Leontief inverse by calculating the inverse of the subtraction of **A** from an identity matrix **I**, mathematically written below:

$$L = \left[l_{ij}\right] = (I - A)^{-1} \tag{2}$$

An identity matrix corresponds to a matrix of equal dimensions to **A**, with ones in the main diagonal and zeros elsewhere, thus $I = \begin{bmatrix} 1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & 1 \end{bmatrix}$. And inverting the matrix requires it to be squared i.e., same number of rows and columns. Finally, the elements l_{ij} in equation 2 represent the total, direct and indirect, output from sector *i* to produce one euro unit of output in sector *j*. The Leontief inverse (**L**) is the backbone of an input-output analysis as it allows the tracing of total input requirements across the supply-chain of production.

2. *Calculate emissions multiplier matrix.*

The GHG data obtained in Exiobase 3 relates to emissions directly produced by a sector. In order to estimate their impact on a consumption-based accounting – and take full stock of indirect consumption – first, the vector of emissions by sector is divided by each industry's total output, thus we obtain, through equation 3, the GHGs per million euros in each industry.

$$d_i' = \left[\frac{g'_i}{x_i}\right] \tag{3}$$

g'_i is a vector of dimensions 1 x 9,800 with each sector's direct GHG pollution. The emissions multiplier, known as the total intensity matrix, gives the direct and indirect GHGs embedded in the entire supply-chain production of a euro value of output by an industry. In order to obtain that, the Leontief inverse can be premultiplied with d_i', which would give a resulting vector of dimensions 1 x 9,800. Nonetheless, this would aggregate all rows, thus in order to obtain detailed results of each sectorial transaction, d_i' is diagonalized into a squared matrix of size 9,800 with the GHGs per million euros displayed in the main diagonal, and zeros elsewhere. The diagonalized form of a vector is represented with a hat, thus we obtain the emissions multiplier matrix as below:

$$M = \left[m_{ij}\right] = \widehat{d_i'} * L \tag{4}$$

Each element m_{ij} provides the direct and indirect GHGs that industry *i* delivers to industry *j* in order for the latter to produce one million euros of output (Kt of CO2-eq/M€). The multiplier matrix **M** is of dimensions 9,800 x 9,800, and thus provides transaction data for each sector in each region analyzed.

3. *Diagonalize final demand categories.*

The final demand (FD) categories provide the final consumptive requirements of non-industrial parts of the economy. The multiplier matrix, on its turn, provides the GHG intensity of production in a given year. Thus, total GHG emissions occurring to satisfy a country's FDs can be obtained by postmultiplying **M** with the respective country's **F** matrix. This would yield the total pollution required by sector to satisfy each of the country's FD, thus resulting in a matrix of 9,800 x 7 dimensions. However, this provides the total consumptive impact of each FD category without a sectorial resolution. In order to obtain the footprints by sector, each FD can be diagonalize and subsequently premultiplied by **M** leading to a matrix of 9,800 x 9,800 which outlines embedded emissions between sectoral transactions. Each FD category is then diagonalized and summed into one matrix of total global final demand $\widehat{Y_{tot}}$.

$$\widehat{Y_{tot}} = \sum_{i=1\ j=1}^{n} \widehat{y_{ij}} \tag{3}$$

$\widehat{y_{ij}}$ represent each FD category *i* in country *j* that is diagonalized, thus in the case of this study, it includes 343 matrices which are added together. The resulting matrix $\widehat{Y_{tot}}$ provides the total final demand of each country in the main diagonal and zeros elsewhere. This matrix is finally premultiplied by **M**, resulting in a 9,800 x 9,800 table outlining the direct and indirect GHGs embedded in the transactions of each sector in and between each country. This is mathematically written below:

$$E = [e_{ij}] = M * \widehat{Y_{tot}} \tag{4}$$

An element e_{ij} in equation 6 provides the total emissions embedded in the total output that sector *i* has to deliver to sector *j* in order for the latter to produce its total output, which will eventually be consumed partially by itself, by other sectors demanding it, and by final consumption categories, such as household consumption and government expenditure.

4. *Obtain sectorial emissions in both consumption and production-based by country.*

The footprint of sectors is obtained by summing the elements e_{ij} over *j*, which are the columns of matrix **E** and represent the input requirements to those sectors. Thus, the total sum of sector *i* in country *j* over its column will include the embedded pollution it consumed from itself, plus from all other domestic sectors in *j*, in addition to all imports. Conversely, the production-based value for each industry is obtained by summing the elements e_{ij} over *i*, which are the rows of matrix **E** and stand for the embedded emissions a sector has produced and delivered to others. In other words, summing sector *i* in country *j* over its row will include embedded pollution it produced to itself, plus all production it delivered domestically, in addition to production exported to other countries' sectors. This can be represented in matrix notation as below:

Footprint of sectors: $\alpha_i = u * E$ (5)

Production-based emissions of sectors: $\beta_i = E * u^T$ (6)

Where u is a vector of dimensions 1 x 9,800 containing only elements equal to one. When u is postmultiplied with **E** it leads to a resulting vector α_i also of dimensions 1 x 9,800 containing the sum of the elements of **E** over its columns. u^T, on its turn, is the transposed form of u and thus has dimensions 9,800 x 1. Premultiplying u^T with **E** results in vector β_i containing the sum of the elements of **E** over its rows. Therefore, the total footprint of sectors aggregated together must equal the total aggregated production-based estimates of sectors, i.e., $\sum_{i=1}^{n} \alpha_i = \sum_{i=1}^{n} \beta_i$. The estimation of sectorial footprint shifts pollution responsibility towards high consuming activities, but it does not alter the global total of pollution.

4.3 Methodology's limitations

Finally, the applied methodology, as with any other study, suffers of some limitations that are worth discussing, particularly for interpreting its results. First, the GMRIO table used includes production and associated emissions for the entire world, but detail data only for 44 countries, where the rest of the world is lumped together into 5 different regions (RoW) aggregating the remaining nations in Europe, Asia, Africa, America, and Middle East (Stadler et al., 2018). This country grouping occurs since not all countries publish IO tables and some regions fall outside the focus of environmental IO analysis, nonetheless they still must be included to ensure consistency in traded goods (Stadler, Steen-Olsen & Wood, 2014). Each of this RoW regions are calculated using proxy data of relatively similar countries, thus their technology-base mirrors to some extent the technology structure of a similar country for where data is available (Stadler, Steen-Olsen & Wood, 2014). IO tables commonly only provide one RoW region, as with WIOD, whereas Exiobase 3 applied in this study addresses some of this uncertainty by splitting it by continent. Nonetheless, uncertainties within each of the RoW analyzed remain a limitation in this study affecting regional differences within these regions and their technological structure.

Secondly, IO tables are built with the assumption that all firms within the same industry are identical in relation to their production process. This is referred to the homogeneity of industrial output and affects the estimations by ultimately assuming that all firms within an industry require the same level of inputs (Lee & Mokhtarian, 2004). This arises due to aggregating different firms within one sectorial classification. In other words, the highest the sectorial resolution, the lower the uncertainties related to analyzing activities with different emissions intensity under the same industrial category. Thirdly, input-output tables assume constant returns to scale, that is, if the output of an industry decreases or rises by x%, then its input requirements should also rise or fall at an equal rate (Lee & Mokhtarian, 2004). Since IO tables provide a source for *ex post* analysis, this assumption limits the extent to what can be forecasted from the results, but it does not significantly affect the estimates of the period under study, since only one actual level of pollution and production took place.

5 Results

This section presents the results obtained from the calculations. Table 5.1 aggregates each regional result into a global value and represent the main finding of this work. Nonetheless, the results are discussed at different levels of regional aggregation. The EU28, large Anglophone countries (United States, Canada, and Australia) and BRIIS (Brazil, Russia, India, Indonesia, and South Africa) were compiled as economic blocks. This study has included the United Kingdom within the EU for allowing comparison with previous studies. The aggregation of Anglophone countries into one block was done following findings in the technology-adjusted consumption-based accounting (TCBA) literature that large former British colonies have a higher carbon intensity of production compared to other developed countries in Europe (Baumert et al., 2019), and thus it is interesting to analyze them separately. China is shown aside from the remaining BRIIS block as its GHG pollution is expected to be significantly higher than other emerging economies.

Table 5.1 The footprint and production pollution of sectors for the year 2017 aggregated at the global level.

Column I	Column II	Column III	Column IV	Column V
Sector code	**Sectors**	**Footprint of sectors (Kt of *CO2*-eq)**	**Production-based emissions of sectors (Kt of *CO2*-eq)**	**% Change between indicators**
c.1	Construction work	7 936 413	456 081	1640%
c.2	Public administration and defence services; compulsory social security services	1 852 857	218 282	749%
c.3	Health and social work services	1 798 099	199 587	801%
c.4	Electricity by coal	1 501 852	6 874 533	-78%
c.5	Machinery and equipment n.e.c.	1 307 080	140 669	829%
c.6	Motor vehicles, trailers, and semi-trailers	1 170 380	97 952	1095%
c.7	Real estate services	1 114 876	191 613	482%
c.8	Food products n.e.c.	1 005 459	159 720	530%
c.9	Motor Gasoline	936 903	367 599	155%
c.10	Hotel and restaurant services	916 906	132 439	592%
c.11	Products of meat cattle	840 521	47 621	1665%
c.12	Electrical machinery and apparatus n.e.c.	671 684	101 881	559%
c.13	Electricity by gas	671 636	1 849 721	-64%
c.14	Chemicals n.e.c.	596 243	1 064 137	-44%
c.15	Education services	583 560	66 876	773%
c.16	Air transport service	548 747	873 742	-37%
c.17	Raw milk	543 769	1 220 504	-55%
c.18	Computer and related services	537 345	50 806	958%
c.19	Furniture; other manufactured goods n.e.c.	495 234	212 353	133%
c.20	Natural gas and services related to natural gas extraction, excluding surveying	494 634	726 712	-32%
c.21	Paddy rice	492 655	1 166 506	-58%
c.22	Radio, television and communication equipment and apparatus	489 011	71 038	588%
c.23	Steam and hot water supply services	487 156	1 368 122	-64%
c.24	Dairy products	476 720	77 722	513%
c.25	Other transport equipment	475 914	79 101	502%
c.26	Processed rice	456 858	43 443	952%
c.27	Wearing apparel; furs	441 780	149 712	195%
c.28	Recreational, cultural, and sporting services	430 023	106 580	303%
c.29	Fish products	392 576	64 089	513%
c.30	Cattle	369 101	2 087 791	-82%
…	…	…	…	…
	Total emissions (Kt of CO2-eq)	40 489 887	40 489 887	

Table 5.1 above provides a snapshot of the results of economic activities aggregated at the global level for the year 2017. It presents the 30 sectors with the highest footprint impacts in decreasing order of their footprint value – indicated by the third column. The remaining 170 sectors are shown in Appendix B. Fourth and fifth columns present respectively the results obtained on a standard production-based accounting, and the percentage difference between the results of two indicators for the same year. The last row of Table 5.1 gives the total impact of all economic sectors, including the remaining activities shown in Appendix B – and it equals the estimations provided by Exiobase 3 (Stadler et al., 2021). The total emissions are the same in the two indicators, reiterating that a footprint approach shifts pollution responsibility to the consuming party, without altering the world total.

Construction work emerged with the largest footprint in the world, accounting for approximately 20% of global emissions in 2017. This is not captured on a standard production-based accounting, which allocates the sector with slightly over 1% of global pollution. Construction work experienced one of the highest increases between indicators, namely 1,640% change (last column of Table 5.1). Construction activities often demand materials (e.g., cement) and high energy inputs, which may embed large GHG emissions. Electricity by coal, on its turn, showed a large decrease when estimating its footprint. Since electricity is a foundational input to most human activities, its pollution content will be assigned to the sectors that demand this source of energy. Food industry sectors such as products of meat cattle, processed rice and dairy products have shown a very large increase. This is expected as industrial food manufacturing requires agricultural inputs, which have on their turn experienced a decrease in response. Cattle, paddy rice and raw milk have all emitted more GHGs than they required for production.

Alongside food industries, service activities have been among the largest insources of GHGs. Public administration and defence, as well as health and social work services have showed respectively an increase of 750% and 800% on their footprint estimations, arriving as the second and third largest demanders of pollution embodied in input requirements in the world. A significant increase in the responsibility for pollution attributed to services is observed across the economic structure, with real state, hotel and restaurants, and educational services being a prominent example. Nonetheless, the same pattern is not observed for transportation services. Most transportation activities, such as air transport in Table 5.1, have had a lower footprint than their production-based estimates. Transportation activities are expected to behave differently than other service provisions in environmental terms and are often analyzed separately from the latter (e.g., Kander, 2005; Alcántara & Padilla, 2009). The reason lies in the fact that many economic activities demand transportation, thus the pollution emitted in this service delivery (i.e., the burning of fuel for transport) is allocated to the sectors that have consumed it. Whereas the pollution embedded in the *production* of fuel itself is assigned to transportation services.

Table 5.1 presented individual country results aggregated at the global level. Figure 5.1 below disaggregates the global values to provide a treemap chart of the footprint of sectors for the EU28. Appendix C shows the footprint of sectors for the remaining country blocks where large Anglophone countries (United States, Canada, and Australia), BRIIS (Brazil, Russia, India, Indonesia, and South Africa) and China are shown. The size of each sector's footprint is represented by the size of the blocks, which contains the industry's name followed by its absolute impact in Kt of CO2-eq. Construction work is the sector with the highest impact in all regions, except in the Anglophone countries where electricity by coal is the highest. Within the EU28, health and social work emerged with the second highest responsibility for pollution in the region (Figure 5.1), and is also high in most regions, except in within the BRIIS block, where a significant share of its total footprint comes from agricultural and food processing sectors (see Appendix C). Service activities comprise many of the top pollutive activities in the EU28 and in the Anglophone countries, whereas China – aside from health care – has a high impact on public administration services. The BRIIS block do not have any services within their ten highest footprints [steam and hot water supply services is often classified under the provision of heating and bundled together with electricity sectors (e.g., Wood et al., 2020b)].

Figure 5.1 Footprint of sectors for the EU28 in Kt of CO2-eq in 2017

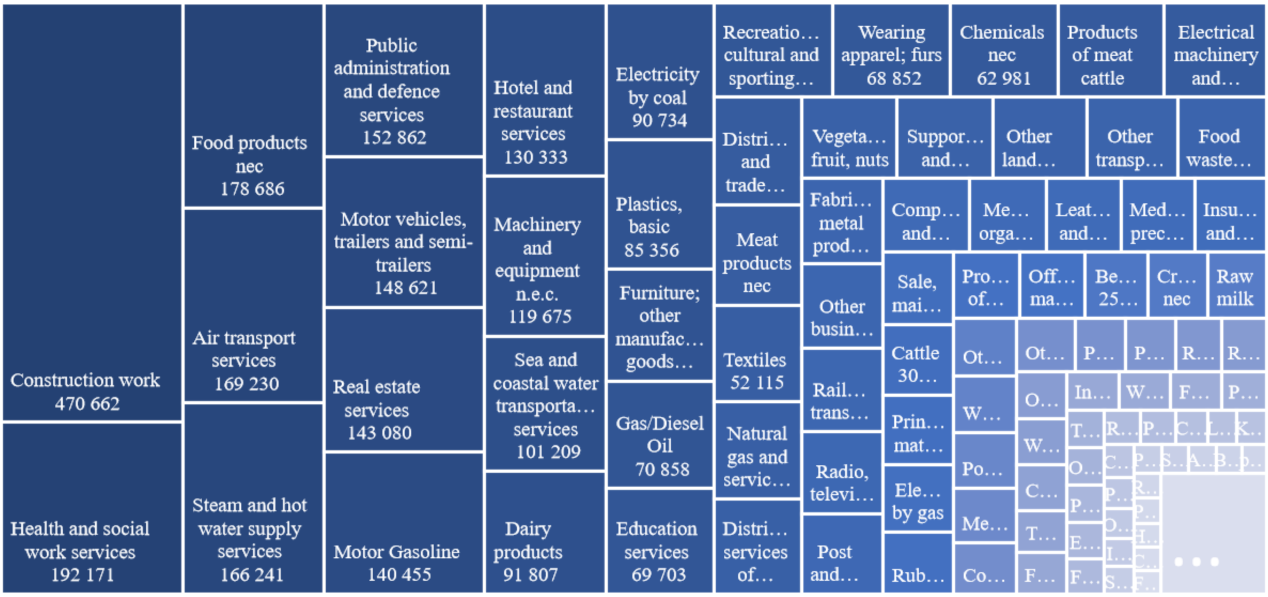


Table 5.2 below provides the results of sectorial footprints per million euros of value added. It also shows the 30 activities with the highest relative level of pollution at the global level in decreasing order. Column I provide the code of each sector derived from Table 5.1, thus for instance, products of meat cattle (c.11) emerged with the second highest pollution per output in the world, but 11th in absolute terms. The last row shows the average relative footprint of all 200 sectors (excluding those that had an aggregate value added of zero). Firstly, from Table 5.2, service activities – in spite of showing a substantial increase in pollution responsibility on their footprint accounts (Table 5.1) – show a very low footprint per million euro of output. Most sectors shown below comprise of agricultural products and industrial processing of food, as well as electricity generation.

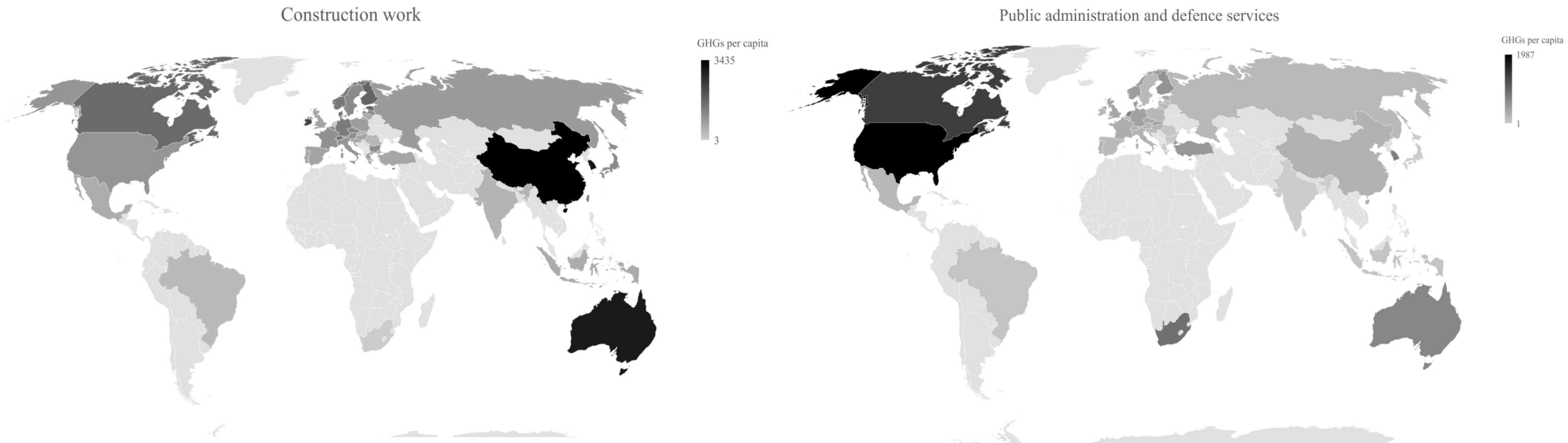
Table 5.2 Footprint relative to sectorial value added aggregated at the global level.

Column I	Column II	Column III
Sector code	**Sectors**	**Footprint per Million Euros (Kt of *CO2*-eq/M€)**
c.23	Steam and hot water supply services	30,93
c.11	Products of meat cattle	25,18
c.87	Biogas	15,79
c.26	Processed rice	14,87
c.166	Electricity by tide, wave, ocean	11,77
c.54	Electricity by petroleum and other oil derivatives	7,51
c.30	Cattle	7,00
c.4	Electricity by coal	6,67
c.13	Electricity by gas	6,50
c.96	Wool, silk-worm cocoons	6,22
c.62	Products of meat pigs	6,00
c.24	Dairy products	5,94
c.53	Meat animals nec	5,13
c.21	Paddy rice	4,25
c.32	Food waste for treatment: landfill	3,96
c.59	Paper for treatment: landfill	3,64
c.9	Motor Gasoline	3,43
c.155	Gas Works Gas	3,34
c.17	Raw milk	2,99

c.20	Natural gas and services related to natural gas extraction, excluding surveying	2,75
c.65	Products of meat poultry	2,59
c.70	Animal products nec	2,47
c.78	Inland water transportation services	2,44
c.99	Other Hydrocarbons	2,44
c.29	Fish products	2,32
c.108	Electricity by biomass and waste	2,22
c.91	Kerosene	2,21
c.100	Textiles waste for treatment: landfill	2,20
c.45	Tobacco products	1,84
c.1	Construction work	1,78
	Economy-wide average	1.53

Tables 5.2 and 5.1 provide a picture of the sectorial footprint results in both relative and absolute terms aggregated at the global level, and thus, highlights the activities with the largest accountability for anthropogenic emissions affecting climate stability. However, it also hides large regional variations, and hence responsibility. Figures 5.2 and 5.3 below provide a regional resolution of, respectively, the four sectors with the highest absolute footprint, and the four sectors with the highest relative footprint. Each map refers to the per capita footprint in each region to allow for country comparisons. They exclude the values obtained from the five rest of the world regions, since they cannot be satisfactorily split by country. However, Appendix D presents the numerical results for these regions, alongside the remaining nations analyzed. Therefore, Figures 5.2 and 5.3 show the detailed results of the 44 countries studied.

Figure 5.2 Per capita footprints of highest sectors by country

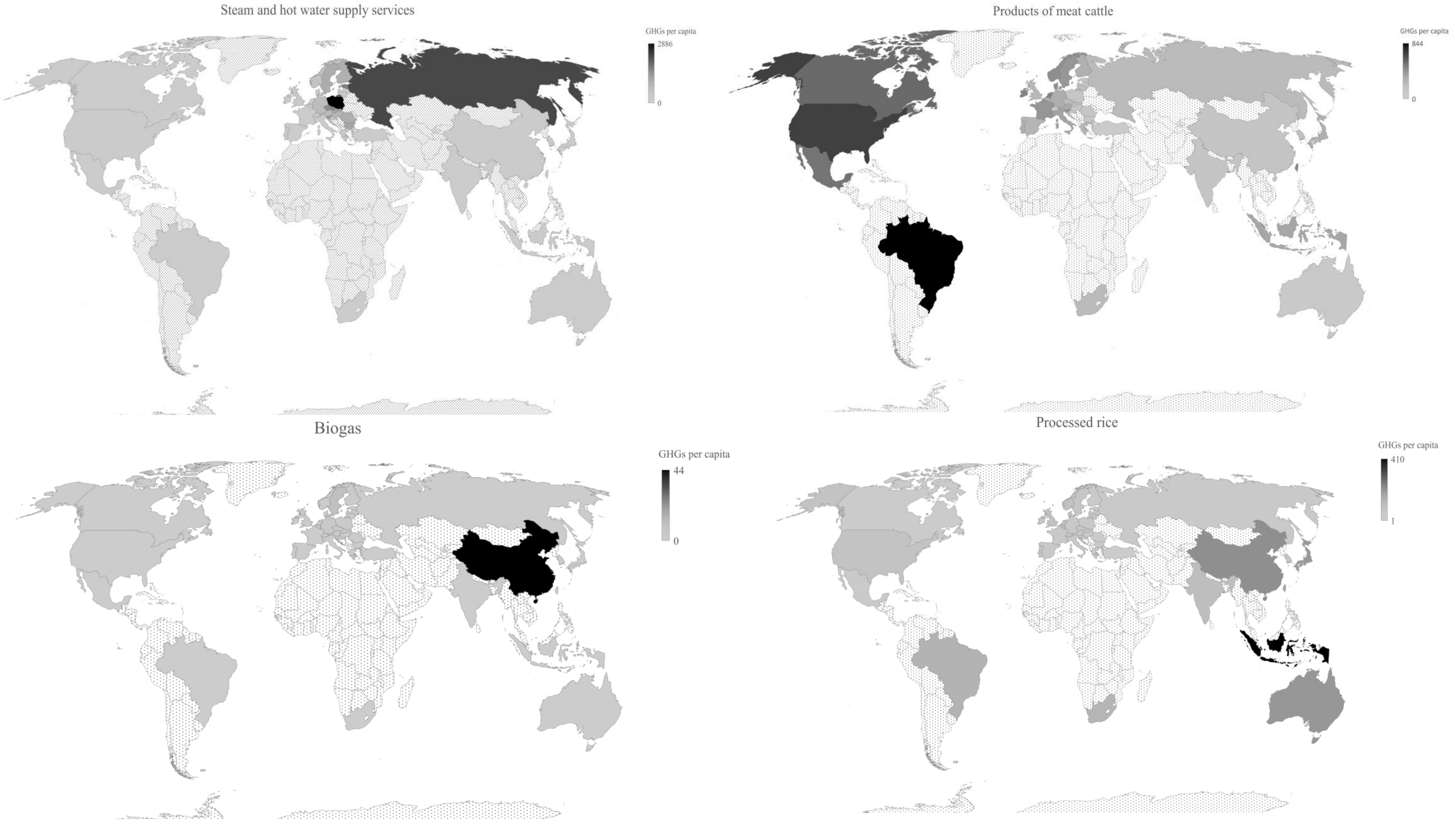

Construction work

Public administration and defence services


Health and social work services

Electricity by coal

Figure 5.3 Per capita footprint of highest sectors relative to value added per country.



The construction work sector in China exhibited the largest per capita footprint on the world with 3,435 Kt of CO2-eq per million people (Kt/Mp.). This was followed respectively by South Korea (3,133 Kt/Mp), Australia (3,008 Kt/Mp) and Ireland (2,319 Kt/Mp) – see Appendix D. South Africa obtained the lowest value with 3 Kt/Mp. The construction work in China alone was responsible for approximately 60% of the global sectorial footprint. The role of other regions in relevant sectors, in terms of their absolute impact, can also be seen in Figure 5.2. The United States and Canada had the largest footprints in public administration and defence services, with respectively 1,987 and 1,404 Kt/Mp. The total impact of the two countries combined corresponds to approximately 38% of the global footprint of the sector. Within health and social work services, the highest per capita footprints observed are concentrated in upper income countries, respectively, Luxembourg (1,655 Kt/Mp), Japan (1,107 Kt/Mp), United States (932 Kt/Mp) and Denmark (923 Kt/Mp).

Figure 5.3 displays the regions where the highest per capita footprints of the sectors with the greatest relative emissions are found. Emissions demanded by steam and hot water supply services are relatively concentrated in a handful of countries. Poland (2,886 Kt/Mp), Russia (1,859 Kt/Mp) and Estonia (1,081 Kt/Mp) are respectively the regions where most of pollution attributed to this sector is demanded. Regarding products of meat cattle, responsibility is more broadly distributed between countries. Brazil (844 Kt/Mp), United States (575 Kt/Mp), and Canada (405 Kt/Mp) emerged with the highest footprints for beef consumption. Biogas, on its turn, had an overall low absolute footprint, of which was almost entirely concentrated in China with 44 Kt/Mp. Pollution demanded by industrial processing of rice is concentrated in Asian Pacific economies with Indonesia (410 Kt/Mp), China (122 Kt/Mp), and Australia (106 Kt/Mp) being the primary demanders.

In order to depict the cause of change between indicators, Figures 5.4 to 5.6 below provide treemap charts outlining the source of input requirements to construction work, public administration and health and social work, respectively. They show the total consumption undertaken by these three activities to deliver their total output, and thus, the underlying makeup of their footprints aggregated at the global level. The size of each industry's contribution to the sector's footprint is represented by the size of the blocks, which contains the industry's name followed by its share in the makeup of the sector's footprint. It can be seen from Figure 5.4 that consumption of cement is the largest source explaining the high impact of construction work, accounting for almost a quarter of its footprint. This is followed by a high consumption of electricity by coal (with 16%), as well as primary industry inputs, such as iron and mineral products. Figures 5.4 to 5.6 outline the causes of high footprints in these sectors, but also hide regional differences. Appendix E presents a snapshot of the top ten sources of inputs consumed by these three sectors, highlighting the country origin of inputs. Production of cement in China alone accounts for roughly 15% of the total global footprint of construction work, followed by inputs of electricity generated by coal-fired plants with 13%, and also in China (see Appendix E).

Figure 5.4 Construction work's consumption of main inputs

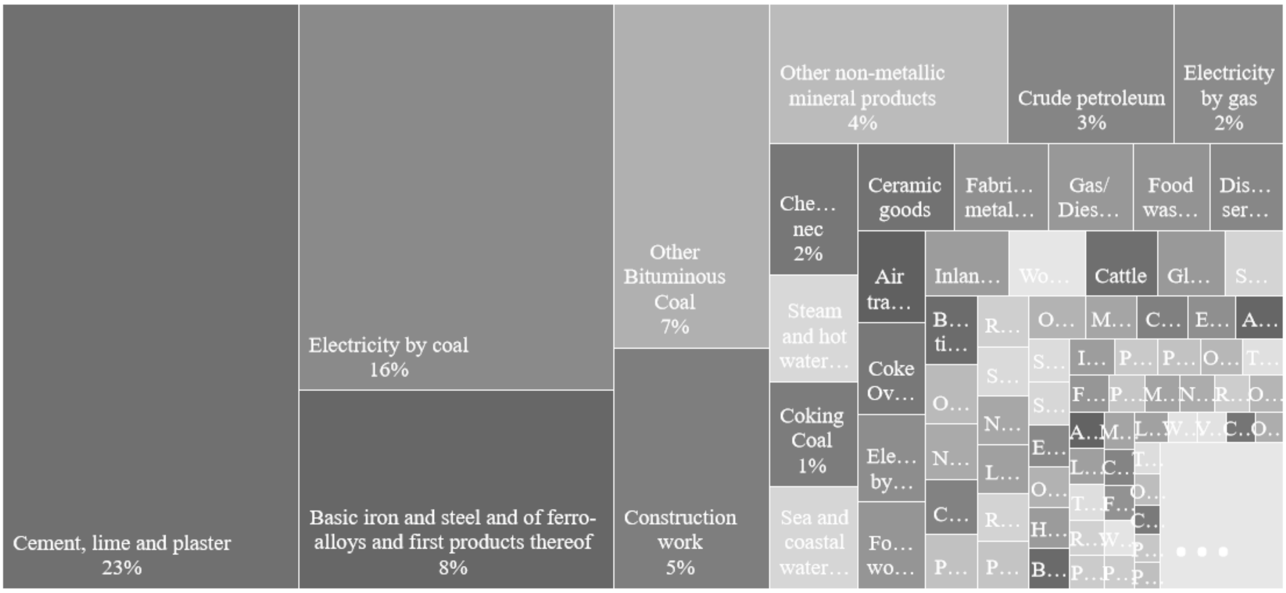


Figure 5.5 Public administration and defence services' consumption of main inputs.

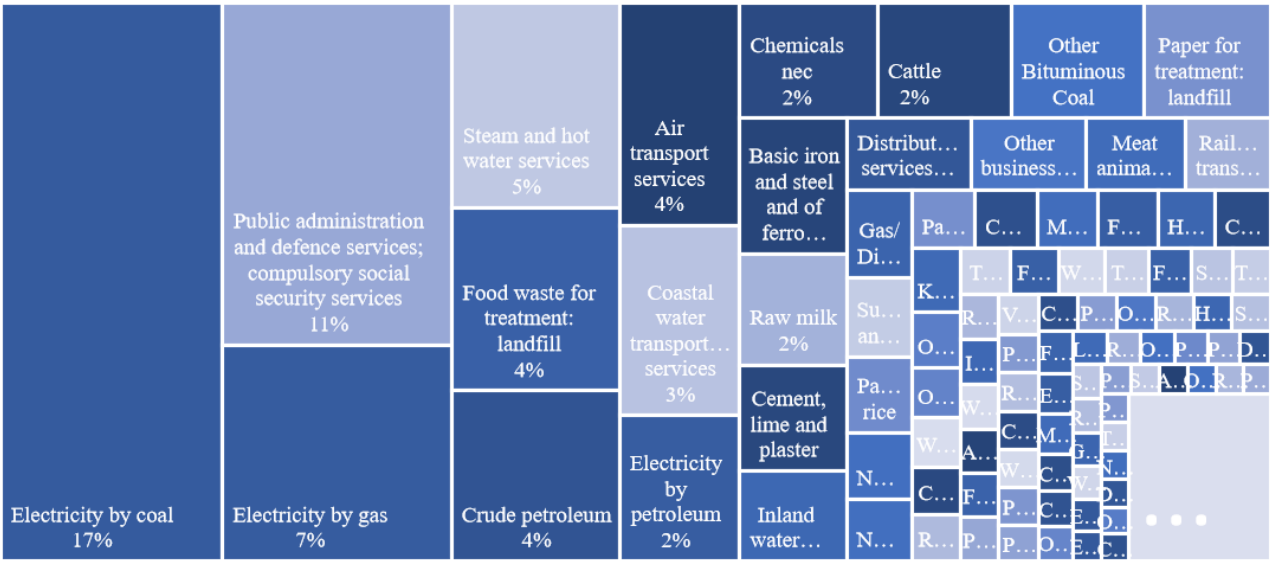


Figure 5.6 Health and social work services' consumption of main inputs.

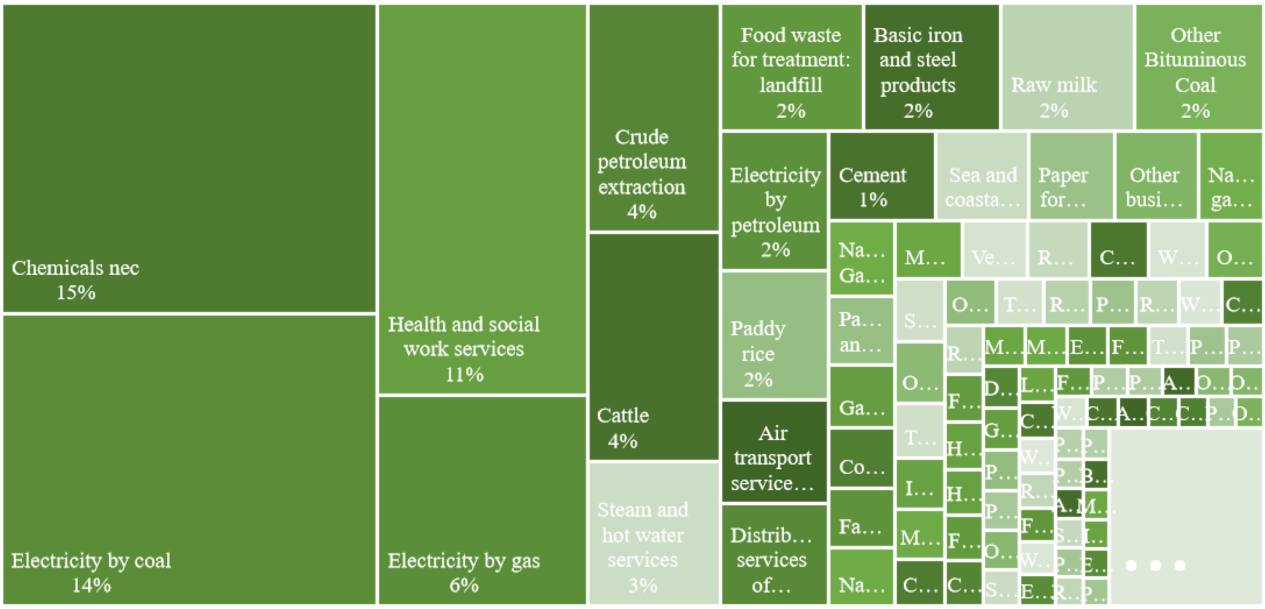


Figure 5.5 reveals that, albeit a significant share of pollution in public administration and defence services is absorption of production within the sector itself (11%), electricity consumption, prominently by coal (17%) and gas (7%), as well as heating (i.e., steam and hot water supply – 5%) are the largest source of increase between indicators in this sector. Consumption of transportation by air and water were also important. Appendix E shows that the largest impacts of electricity by coal for public administration occur in the United States and China, respectively. Finally, Figure 5.6 depicts the intake of inputs in the health and social work sectors. Consumption of embedded emissions from chemical industries as well as from the health sector itself account together for approximately 26% of the sector's footprint, while electricity by coal and gas account for 20% combined. Health and social work also exhibit significant pollution embedded petroleum related products (4%), as well as agricultural goods, such as cattle (4%), paddy rice (2%) and milk (2%). China, United States, the RoW Middle East and Japan are the main contributors to the absolute footprint of health services (see Appendix E).

6 Discussion

6.1 Implications of Results

The present paper was, to the author's knowledge, the first work to address cross-sector carbon leakage at the global level by estimating the footprint of sectors and analyzing the results in contrast to standard production methods. It provides the most comprehensive sectorial consumption analysis taken to date through the examination of 200 economic activities in 44 countries and 5 Rest of the World regions (RoW) covering the remaining nations. At the European Union level (EU28), Wood et al. (2020b), using the same dataset as this work and analyzing the year 2016, found that construction work and health services were respectively the second and third sectors with the highest footprint in the region, whereas electricity consumption was the first.

Nonetheless, this study has shown that the sectors with the largest impact in the region were respectively construction work, health and social work services and food products n.e.c. (Appendix D). The first sector generating electricity (by coal) appears in 14th place with approximately 2% of the region's footprint. Wood et al. (2020b) have aggregated all electricity producing sectors as well as steam and hot water supply services into a category defined as 'electricity and heat'. Nonetheless, this no longer becomes comparable with the remaining disaggregated industries. For instance, food industry products can also be put together into one sector, and they will emerge with a higher footprint than construction work in EU28, thus, shifting policy priorities based on such result. Therefore, this paper is in line with Wood et al.'s (2020b) findings regarding the high impact of construction work and health services in Europe, which also emerged with high absolute footprints (see Figure 5.1) but rejects the authors conclusions on the region's electricity consumption, which must be analyzed at the same level of aggregation as the remaining sectors.

The results have also highlighted that service activities have experienced a considerable increase between estimators, contradicting early studies emphasizing an environmental improvement through the expansion of the service economy (e.g., Pacala & Socolow, 2004;

Panayotou, Peterson & Sachs, 2000). Consumption of fossil fuel-based electricity was among the main causes of an increase in the share of pollution responsibility of services, nonetheless, services have also demanded pollution across the economic structure, such as through chemical production for health care provision, and agricultural and food industry goods for hotels and restaurants. Thus, albeit it is plausible to expect the footprint of services to significantly reduce upon an increase in the share of renewable electricity provision, the expansion of services will also likely lead to an expansion for its input requirements, thus suggesting a similar view as those proposed by Suh (2006) and Parrique et al. (2019), of services happening on "top" of the economic structure, meaning adding environmental pressure, rather than substituting it.

6.2 Policy Relevance

Construction work emerged as a significant priority for emissions mitigation for its consumption is responsible for the largest share of anthropogenic emissions. Whilst China's footprint accounts for most of the sector's pollution, with a total impact of 4 683 203 Kt of CO2-eq, if we exclude China of the estimates, construction work remains the most pollutive sector of the global economy with almost twice the footprint of the second largest emitter (i.e., public administration and defence services). The large use of cement was found to be the main cause of the industry's footprint, followed by electricity consumption. This finding can significantly contribute to the design of effective mitigation policies. First, the high impact of cement highlights the need for restructuring infrastructure projects related to housing and buildings, where cement is broadly used. Alternative materials, such as wood and, more recently green steal, can assist in reducing reliance in cement, in addition to carbon intensity improvements during the production process of the industry. However, it is beyond the scope of this work to quantitatively compare mitigation potentials of different approaches, but to highlight the sectors where policies must focus.

In addition, cement indirectly affects policies involving other industries. For instance, the transportation sector indirectly benefits from construction work. Roads, bridges, and tunnels make use of large amounts of cement. Nonetheless, policies attempting to address the impact of transportation have focused so far on the direct fuel burning during commuting (e.g., Moran et al., 2020). Moreover, as the results have shown, motor vehicles, trailers, and semi-trailers (c.6) emerged as the 6th largest polluter and with one of the largest increases between estimations, with 1,095% change. This highlights that a considerable impact lies during the production phase of the vehicles themselves, rather than during its usage. Therefore, policies to foster the implementation of electric vehicles (EV) for instance, do not address the main impacts revolving transportation, namely, a high demand for large scale infrastructure from construction work, and the production process of vehicles. A consumption-based approach highlights the interlinkages of sectors, contributing to a holistic approach to mitigation strategies. Based on the results, the transportation sector should not pursue policies that lower its direct impact but maintain or increase indirect pollution in other industries.

The footprint estimations in this study have also stressed the impact of public administration and defence and health and social work service. These sectors are given little police and academic attention regarding its pollution impacts since a production-based approach assigns them with approximately 0.5% of global pollution each, whereas under a footprint estimation, they are responsible respectively for 4.6% and 4.4% of global emissions. On the one hand, the main cause of public administration’s high footprint is due to its fossil-fuel based electricity consumption, reiterating that electricity is a foundational input to all economic activities, thus phasing out non-renewable energy sources should be a priority policy that will affect all sectors. On the other hand, health services footprint is largely the result of high chemicals consumption and transactions within the sector itself, thus even if energy related emissions are phased out, this sector is likely to continue exerting significant pressure. Albeit the ongoing Covid-19 outbreak may have temporarily reduced pollution in the initial stages of the crisis (Le Quéré et al., 2020), the prolonged increase in health service provision is expected to increase the demand for its input requirements, which have likely offset part of the emissions reduction during this period. Policies, therefore, need to increasingly address the climate impact of health provision under a consumption-based approach.

7 Conclusion

7.1 Summary

This essay set out to investigate the responsibility of sectors for greenhouse gas emissions under a consumption-based approach for the year 2017. In doing so, it aimed to address cross-sector carbon leakage by analyzing footprint estimates in relation to standard production-based values and uncover the cause of emissions responsibility change between the two indicators. This, on its turn, sought to contribute to the understanding of interlinkages between different economic activities and how this affects emissions mitigation strategies. Therefore, the present study addressed the following questions:

I. *What were the greenhouse gas footprint of sectors at the global level, both in absolute terms and relative to their economic output in the year 2017?*
   a. *In which regions did the most polluting sectors exhibit the highest per capita footprint?*

II. *What were the underlying consumption activities causing a shift in the responsibility of the sectors with the highest footprints?*

The results have identified substantial change between indicators, and thus pollution responsibility. Generally, primary industries such as mining, agriculture, but also electricity production have seen a decrease in responsibility, as their embedded emissions were transferred to consuming sectors, such as manufacturing, food processing and services. Construction work has seen a 17-fold increase in its responsibility and emerged with the highest absolute footprint in the world, accounting for approximately 20% of GHG emissions globally. Notwithstanding the fact that China drove most of the consumption for construction work – being responsible for roughly 60% of the sector's footprint – the industry remains the largest polluter in the world, even if we exclude the Asian economy from the estimates. Service activities, on their turn, also experienced significant increases, where public administration, and health and social work were respectively the 2nd and 3rd most pollutive sectors in the economy. The impact of services is most prominent in high-income countries, whereas emerging economies saw a high impact of agricultural and food processing goods instead.

The footprint of sectors relative to their economic output showed that steam and hot water supply services, used for heating purposes, was the sector with the highest greenhouse gas intensity per million euros of value added. Agricultural and food processing food, nonetheless, made the majority of sectors with high pollution intensity, highlighting a need to improve the production process of these sectors' input requirements, mostly consisting of agricultural food products. Finally, within the sectors with the highest footprints, consumption of cement was the largest cause of increase in indicators for construction work, followed by a high consumption of electricity by coal. Electricity, on its turn, was the most prominent consumption category explaining an increase in services at large (including public administration). Nonetheless, consumption of chemical products had the largest impact explaining changes in health and social work.

7.2 Limitations and Areas for Future Research

Notwithstanding that this study conducted a detailed processing of data to reach its aims, this essay has limitations that constrain the extent of what can be concluded from the results, and thus are relevant to be discussed. Firstly, as all IO studies, the GHG data analyzed does not include Land Use and Land Use Change and Forestry (LULUCF) emissions, such as deforestation and soil burning practices. This is an error that arises from the choice of methodology since IO tables do not include LULUCF pollution due to the difficulty of assigning these emissions to productive sectors of the economy in a yearly basis (Wood et al., 2020b). Including these emissions would primarily alter the total impact of agricultural goods, and as a consequence, the footprint of food industries and services, such as hotels and restaurants. Under a production-based accounting, omitting LULUCF would affect sectors only within countries where such practices represent a high share of the nation's emissions. Nonetheless, under a consumption-based approach, this affects the imports of nations that consume products with such embedded emissions. However, the inclusion of LULUCF would require a different methodological approach, which could undermine a sectorial footprint analysis for which IO tables are a robust method to use.

Secondly, this study has assigned full pollution responsibility to consuming parties, which may be argued to be suboptimal. Approaches to which responsibility is shared may be viewed as more conductive to fairer policy formulations. Kander et al. (2015), for instance, argued that under a consumption-based accounting, countries that improve their carbon intensity of export industries are not credited since the improve in emissions is assigned to consuming nations instead. Third, the emissions intensity values of each sector per economic output does not divide each sector by their *total sales value*, but by their *value added* instead. Total sales value includes the price paid by the input requirements, and thus are more appropriate to use when estimating the consumption of sectors. Compiling data on total sales value that matches the sectorial resolution of Exiobase would have consumed a significant amount of time and thus was not performed in this study. Therefore, the GHG intensity of sectors should be seen as tentative and interpreted with caution.

Finally, venues for future research include addressing some of the limitations of this study, such as adjusting for technological differences in export industries to avoid full responsibility of consuming parties, and adjusting sectorial pollution with more appropriate monetary data, as well as modelling IO analysis with LULUCF emissions. But also includes further investigation into the results obtained in paper. For instance, cross-sector carbon leakage was shown to be very substantial, and albeit this paper set out to highlight regional variations, future research can expand this analysis to provide data into how such concealing of emissions affects individual countries, thus providing more direct policy recommendations at the national level. In addition, health care provision emerged highly emissions intensive, prominently in upper-income countries. Hence, how a prolonged rise in demand for health provision during the Covid-19 outbreak has affected the footprint of the sector, and whether this has substantially offset emissions reductions from confinement during the period, is a relevant area for investigation.

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Appendix A

Table A.1: Exiobase 3 country coverage.

Code	Country
AT	Austria
BE	Belgium
BG	Bulgaria
CY	Cyprus
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
ES	Spain
FI	Finland
FR	France
GR	Greece
HR	Croatia
HU	Hungary
IE	Ireland
IT	Italy
LT	Lithuania
LU	Luxembourg
LV	Latvia
MT	Malta
NL	Netherlands
PL	Poland
PT	Portugal
RO	Romania
SE	Sweden

Code	Country
SI	Slovenia
SK	Slovakia
GB	United Kingdom
US	United States
JP	Japan
CN	China
CA	Canada
KR	South Korea
BR	Brazil
IN	India
MX	Mexico
RU	Russia
AU	Australia
CH	Switzerland
TR	Turkey
TW	Taiwan
NO	Norway
ID	Indonesia
ZA	South Africa
WA	RoW Asia
WL	RoW America
WE	RoW Europe
WF	RoW Africa
WM	RoW Middle East

Appendix B

Table B.1: The footprint and production pollution of sectors for the year 2017 aggregated at the global level.

Column I	Column II	Column III	Column IV	Column V
Sector code	**Sectors**	**Global footprint of sectors (Kt of *CO2*-eq)**	**Global production pollution of sectors (Kt of *CO2*-eq)**	**% Change**
c.31	Other services (93)	354 358	34 039	941%
c.32	Food waste for treatment: landfill	337 046	996 790	-66%
c.33	Vegetables, fruit, nuts	333 176	326 339	2%
c.34	Membership organisation services n.e.c. (91)	320 003	102 141	213%
c.35	Textiles (17)	314 358	163 308	92%
c.36	Distribution and trade services of electricity	301 160	54 471	453%
c.37	Other land transportation services	296 680	75 580	293%
c.38	Fabricated metal products, except machinery and equipment (28)	257 496	301 255	-15%
c.39	Insurance and pension funding services, except compulsory social security services (66)	254 336	38 471	561%
c.40	Beverages	241 794	48 942	394%
c.41	Office machinery and computers (30)	233 917	17 925	1205%
c.42	Distribution services of gaseous fuels through mains	233 516	495 962	-53%
c.43	Sea and coastal water transportation services	227 064	617 212	-63%
c.44	Gas/Diesel Oil	213 477	313 797	-32%
c.45	Tobacco products (16)	207 206	171 012	21%
c.46	Supporting and auxiliary transport services; travel agency services (63)	203 268	194 806	4%
c.47	Other business services (74)	201 906	230 346	-12%
c.48	Post and telecommunication services (64)	199 628	59 384	236%
c.49	Medical, precision and optical instruments, watches and clocks (33)	196 601	43 359	353%
c.50	Other waste for treatment: waste water treatment	178 840	219 960	-19%
c.51	Collected and purified water, distribution services of water (41)	178 163	82 084	117%
c.52	Rubber and plastic products (25)	175 414	122 298	43%
c.53	Meat animals nec	174 658	279 003	-37%
c.54	Electricity by petroleum and other oil derivatives	172 097	620 147	-72%
c.55	Wheat	171 255	230 113	-26%
c.56	Leather and leather products (19)	167 000	29 134	473%
c.57	Railway transportation services	166 453	179 739	-7%
c.58	Research and development services (73)	162 177	81 520	99%
c.59	Paper for treatment: landfill	160 536	388 598	-59%

Column I	Column II	Column III	Column IV	Column V
Sector code	**Sectors**	**Global footprint of sectors (Kt of *CO2*-eq)**	**Global production pollution of sectors (Kt of *CO2*-eq)**	**% Change**
c.60	Meat products nec	152 934	51 261	198%
c.61	Crops nec	141 806	169 625	-16%
c.62	Products of meat pigs	132 630	43 897	202%
c.63	Paper and paper products	131 188	149 103	-12%
c.64	Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods (52)	129 876	55 879	132%
c.65	Products of meat poultry	127 051	37 749	237%
c.66	Printed matter and recorded media (22)	122 628	53 596	129%
c.67	Food waste for treatment: waste water treatment	121 191	150 078	-19%
c.68	Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries	117 119	37 019	216%
c.69	Financial intermediation services, except insurance and pension funding services (65)	117 118	93 779	25%
c.70	Animal products nec	113 687	39 678	187%
c.71	Crude petroleum and services related to crude oil extraction, excluding surveying	110 705	1 751 412	-94%
c.72	Poultry	102 272	131 446	-22%
c.73	Basic iron and steel and of ferro-alloys and first products thereof	99 980	1 816 022	-94%
c.74	Plastics, basic	98 613	83 996	17%
c.75	Wholesale trade and commission trade services, except of motor vehicles and motorcycles (51)	96 191	89 421	8%
c.76	Cereal grains nec	93 696	262 935	-64%
c.77	Private households with employed persons (95)	79 612	3 498	2176%
c.78	Inland water transportation services	73 661	234 498	-69%
c.79	Other non-metallic mineral products	71 263	497 079	-86%
c.80	Renting services of machinery and equipment without operator and of personal and household goods (71)	69 584	92 886	-25%
c.81	Liquefied Petroleum Gases (LPG)	69 084	65 693	5%
c.82	Services auxiliary to financial intermediation (67)	68 346	42 476	61%
c.83	Other Bituminous Coal	68 171	1 362 939	-95%
c.84	Natural Gas Liquids	66 635	244 268	-73%
c.85	Wood and products of wood and cork (except furniture); articles of straw and plaiting materials (20)	64 584	129 919	-50%
c.86	products of Vegetable oils and fats	64 181	29 240	119%
c.87	Biogas	60 733	59 043	3%
c.88	Transmission services of electricity	60 542	31 027	95%
c.89	Pigs	53 439	144 891	-63%

Column I	Column II	Column III	Column IV	Column V
Sector code	**Sectors**	**Global footprint of sectors (Kt of *CO2*-eq)**	**Global production pollution of sectors (Kt of *CO2*-eq)**	**% Change**
c.90	Ceramic goods	49 389	125 508	-61%
c.91	Kerosene	48 514	26 315	84%
c.92	Sugar	40 919	12 756	221%
c.93	Transportation services via pipelines	39 866	144 089	-72%
c.94	Oil seeds	32 341	140 532	-77%
c.95	Fish and other fishing products; services incidental of fishing (05)	31 439	20 202	56%
c.96	Wool, silk-worm cocoons	31 101	52 287	-41%
c.97	Products of forestry, logging and related services (02)	30 772	44 763	-31%
c.98	Foundry work services	30 268	194 949	-84%
c.99	Other Hydrocarbons	29 624	58 474	-49%
c.100	Textiles waste for treatment: landfill	28 299	78 426	-64%
c.101	Cement, lime and plaster	25 265	2 069 954	-99%
c.102	Plastic waste for treatment: landfill	23 654	40 485	-42%
c.103	Glass and glass products	22 959	112 808	-80%
c.104	Heavy Fuel Oil	21 409	98 287	-78%
c.105	Wood waste for treatment: landfill	19 616	51 609	-62%
c.106	P- and other fertiliser	19 023	77 264	-75%
c.107	Retail trade services of motor fuel	18 839	28 996	-35%
c.108	Electricity by biomass and waste	18 111	48 686	-63%
c.109	Kerosene Type Jet Fuel	16 358	40 387	-59%
c.110	Electricity by nuclear	15 408	4 930	213%
c.111	Lead, zinc and tin ores and concentrates	13 852	52 986	-74%
c.112	Sugar cane, sugar beet	13 259	49 724	-73%
c.113	Inert/metal/hazardous waste for treatment: landfill	13 026	5 503	137%
c.114	Aluminium and aluminium products	12 724	72 490	-82%
c.115	Precious metals	12 577	37 131	-66%
c.116	Plastic waste for treatment: incineration	11 962	30 794	-61%
c.117	Copper products	11 690	71 215	-84%
c.118	Food waste for treatment: composting and land application	11 485	11 572	-1%
c.119	Paper waste for treatment: incineration	11 446	7 872	45%
c.120	Uranium and thorium ores (12)	11 409	24 641	-54%
c.121	Intert/metal waste for treatment: incineration	11 330	32 495	-65%
c.122	Coke Oven Coke	11 245	189 141	-94%

Column I	Column II	Column III	Column IV	Column V
Sector code	**Sectors**	**Global footprint of sectors (Kt of *CO2*-eq)**	**Global production pollution of sectors (Kt of *CO2*-eq)**	**% Change**
c.123	Lead, zinc and tin and products thereof	10 665	20 535	-48%
c.124	Food waste for treatment: incineration	10 336	7 403	40%
c.125	Copper ores and concentrates	10 234	72 501	-86%
c.126	Pulp	9 933	36 540	-73%
c.127	Coking Coal	9 732	305 199	-97%
c.128	Electricity by hydro	9 714	9 248	5%
c.129	Additives/Blending Components	8 182	4 764	72%
c.130	Sewage sludge for treatment: biogasification and land application	8 166	5 536	48%
c.131	Other non-ferrous metal products	7 738	80 627	-90%
c.132	Nuclear fuel	7 427	6 584	13%
c.133	Plant-based fibers	7 224	53 177	-86%
c.134	Precious metal ores and concentrates	6 826	63 017	-89%
c.135	Iron ores	6 339	57 462	-89%
c.136	Electricity nec	6 307	81 223	-92%
c.137	Oil/hazardous waste for treatment: incineration	6 287	22 055	-71%
c.138	Chemical and fertilizer minerals, salt and other mining and quarrying products n.e.c.	6 182	29 658	-79%
c.139	Textiles waste for treatment: incineration	5 537	25 765	-79%
c.140	Lignite/Brown Coal	5 113	29 177	-82%
c.141	Anthracite	4 846	62 097	-92%
c.142	Secondary raw materials	4 768	84 081	-94%
c.143	Sand and clay	4 160	68 179	-94%
c.144	Wood waste for treatment: incineration	4 063	3 884	5%
c.145	Naphtha	3 799	52 199	-93%
c.146	Stone	3 226	43 812	-93%
c.147	Other non-ferrous metal ores and concentrates	2 747	59 084	-95%
c.148	Aluminium ores and concentrates	2 641	26 949	-90%
c.149	Paper and wood waste for treatment: composting and land application	2 447	1 546	58%
c.150	Lubricants	2 380	17 889	-87%
c.151	Charcoal	2 338	4 799	-51%
c.152	Biogasoline	2 122	3 976	-47%
c.153	N-fertiliser	1 864	11 690	-84%
c.154	Food waste for treatment: biogasification and land application	1 864	1 687	11%

Column I	Column II	Column III	Column IV	Column V
Sector code	**Sectors**	**Global footprint of sectors (Kt of *CO2*-eq)**	**Global production pollution of sectors (Kt of *CO2*-eq)**	**% Change**
c.155	Gas Works Gas	1 768	3 864	-54%
c.156	Bricks, tiles and construction products, in baked clay	1 742	45 902	-96%
c.157	Coke oven gas	1 528	24 533	-94%
c.158	Electricity by wind	1 510	16 187	-91%
c.159	Petroleum Coke	1 180	4 068	-71%
c.160	Non-specified Petroleum Products	1 064	8 471	-87%
c.161	Nickel ores and concentrates	1 053	43 306	-98%
c.162	BKB/Peat Briquettes	991	3 791	-74%
c.163	Biodiesels	691	1 966	-65%
c.164	Bitumen	687	12 216	-94%
c.165	Peat	637	1 767	-64%
c.166	Electricity by tide, wave, ocean	615	12 869	-95%
c.167	Electricity by solar photovoltaic	607	6 313	-90%
c.168	Paraffin Waxes	367	4 501	-92%
c.169	Electricity by Geothermal	364	6 398	-94%
c.170	White Spirit & SBP	355	6 283	-94%
c.171	Patent Fuel	333	3 460	-90%
c.172	Coal Tar	299	15 352	-98%
c.173	Refinery Feedstocks	259	16 755	-98%
c.174	Ethane	258	2 970	-91%
c.175	Other Liquid Biofuels	220	646	-66%
c.176	Sub-Bituminous Coal	215	32 514	-99%
c.177	Refinery Gas	205	3 834	-95%
c.178	Blast Furnace Gas	194	54 407	-100%
c.179	Paper waste for treatment: biogasification and land application	147	795	-82%
c.180	Aviation Gasoline	90	861	-90%
c.181	Gasoline Type Jet Fuel	24	2 353	-99%
c.182	Electricity by solar thermal	4	2 314	-100%
c.183	Oxygen Steel Furnace Gas	0	1 111	-100%
c.184	Gas Coke	0	1 448	-100%
c.185	Manure (conventional treatment)	-	-	
c.186	Manure (biogas treatment)	-	-	

Column I	Column II	Column III	Column IV	Column V
Sector code	**Sectors**	**Global footprint of sectors (Kt of *CO2*-eq)**	**Global production pollution of sectors (Kt of *CO2*-eq)**	**% Change**
c.187	Wood material for treatment, Re-processing of secondary wood material into new wood material	-	-	
c.188	Secondary paper for treatment, Re-processing of secondary paper into new pulp	-	-	
c.189	Secondary plastic for treatment, Re-processing of secondary plastic into new plastic	-	-	
c.190	Secondary glass for treatment, Re-processing of secondary glass into new glass	-	-	
c.191	Ash for treatment, Re-processing of ash into clinker	-	-	
c.192	Secondary steel for treatment, Re-processing of secondary steel into new steel	-	-	
c.193	Secondary preciuos metals for treatment, Re-processing of secondary preciuos metals into new preciuos metals	-	-	
c.194	Secondary aluminium for treatment, Re-processing of secondary aluminium into new aluminium	-	-	
c.195	Secondary lead for treatment, Re-processing of secondary lead into new lead	-	-	
c.196	Secondary copper for treatment, Re-processing of secondary copper into new copper	-	-	
c.197	Secondary other non-ferrous metals for treatment, Re-processing of secondary other non-ferrous metals into new other non-ferrous metals	-	-	
c.198	Bottles for treatment, Recycling of bottles by direct reuse	-	-	
c.199	Secondary construction material for treatment, Re-processing of secondary construction material into aggregates	-	-	
c.200	Extra-territorial organizations and bodies	-	-	
	Total Global GHG emissions	40 489 887	40 489 887	

Appendix C

Figure D.2: Footprint of sectors for Anglophone countries (excluding United Kingdom) in Kt of CO2-eq in 2017

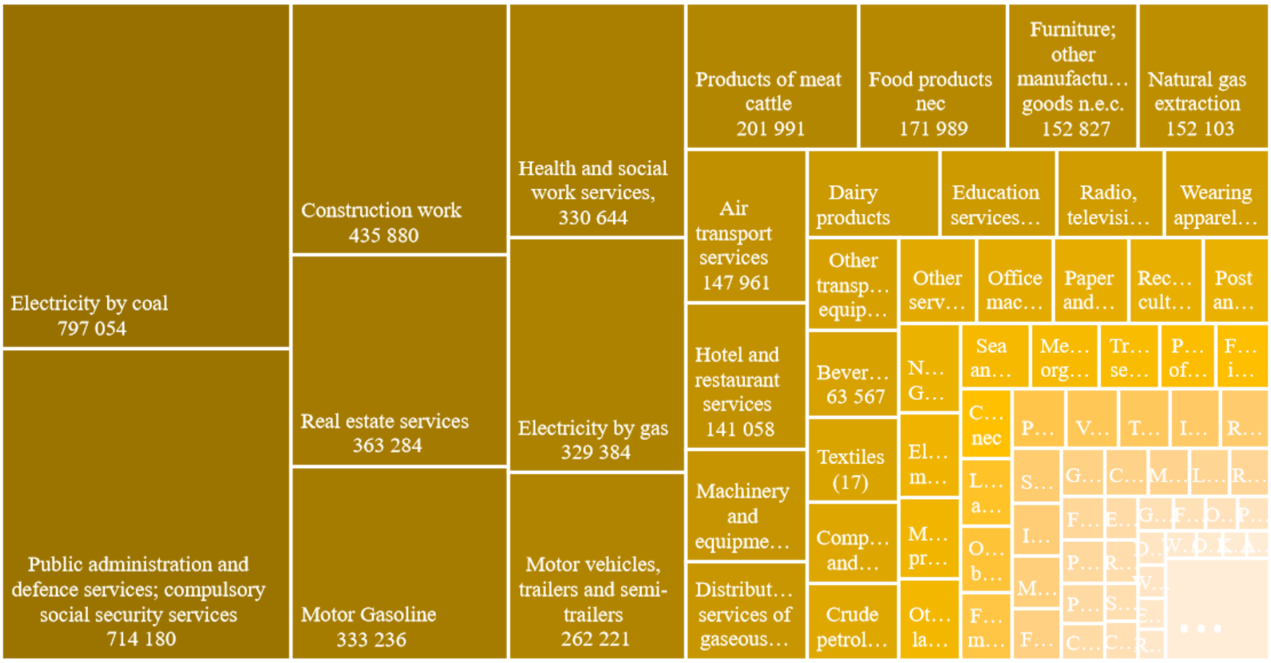


Figure D.3: Footprint of sectors for BRIIS countries (Brazil, Russia, India, Indonesia and South Africa) in Kt of CO2-eq in 2017

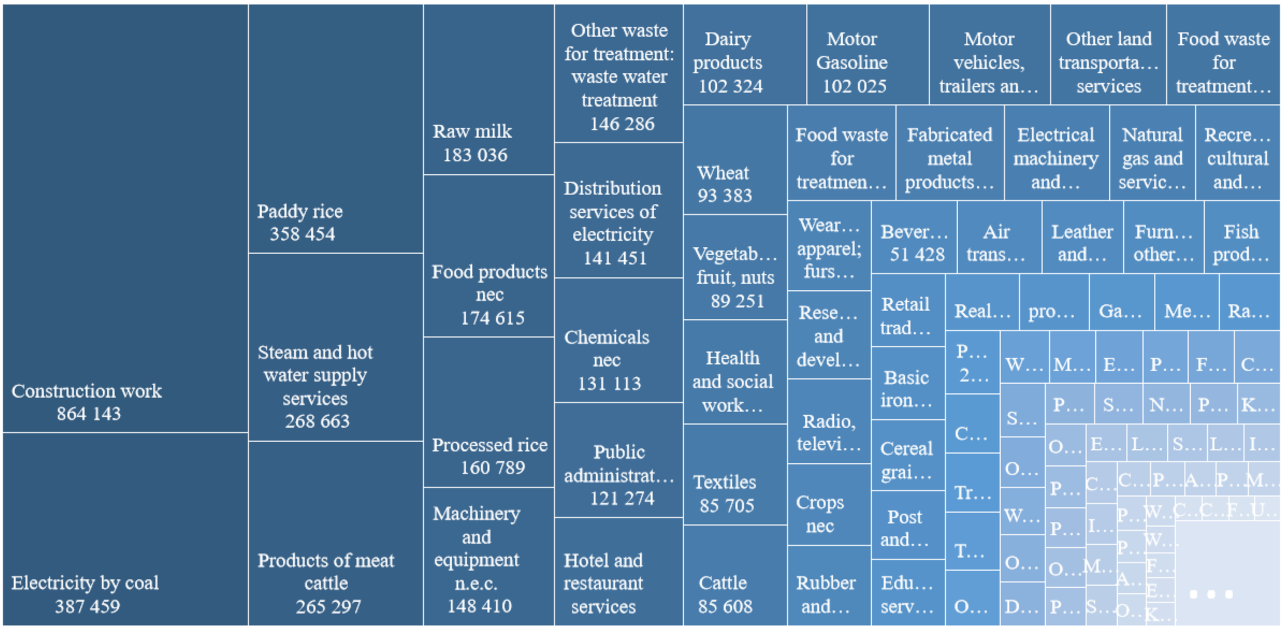
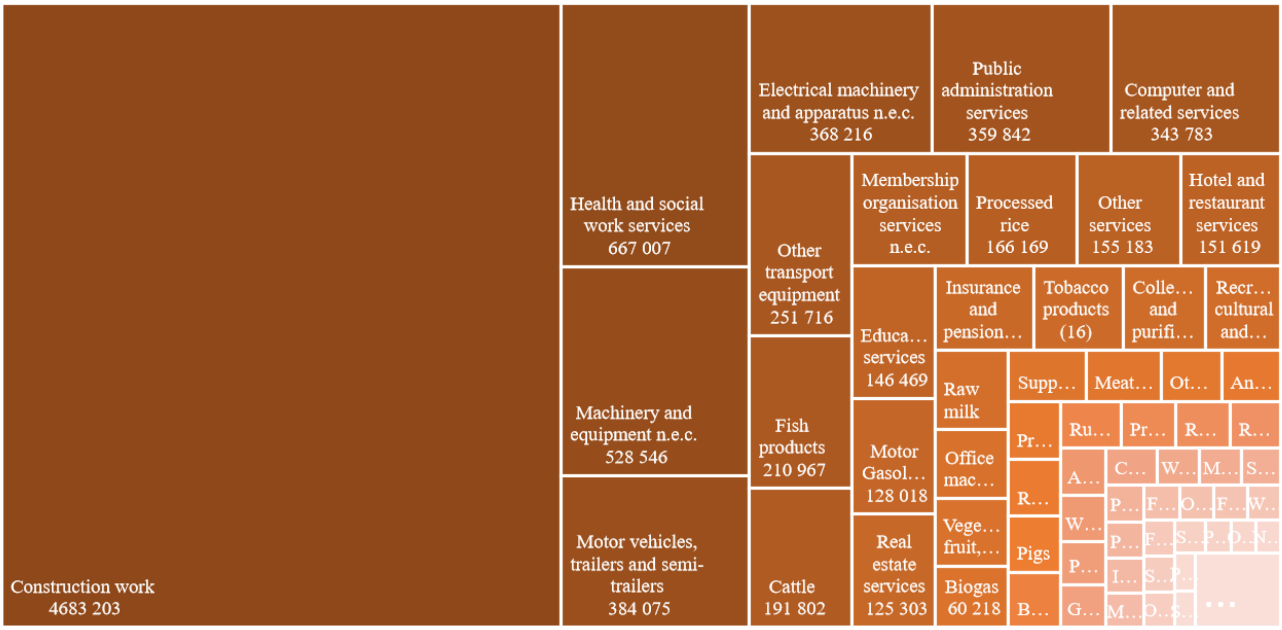


Figure D.4: Footprint of sectors for China in Kt of CO2-eq in 2017



Appendix D

Table D.1: Per capita footprint of top polluting sectors

Country	Construction work	Public administration and defence services	Health and social work services	Electricity by coal
Austria	1 066	215	282	67
Belgium	1 113	191	664	98
Bulgaria	1 101	49	226	3
Cyprus	1 706	344	242	0
Czech Republic	1 188	346	255	236
Germany	1 344	415	541	499
Denmark	1 507	447	923	0
Estonia	1 782	357	287	3 194
Spain	676	166	304	216
Finland	1 748	570	497	167
France	987	306	323	69
Greece	673	13	208	948
Croatia	944	274	111	9
Hungary	694	222	241	170
Ireland	2 319	204	212	8
Italy	944	264	276	0
Lithuania	567	192	81	0
Luxembourg	1 725	412	1 655	0
Latvia	1 042	130	104	0
Malta	94	700	774	0
Netherlands	105	751	541	3
Poland	817	209	184	143
Portugal	630	243	238	335
Romania	372	61	179	157
Sweden	1 109	184	226	0
Slovenia	714	211	290	130
Slovakia	458	412	214	43
United Kingdom	670	377	573	17
United States	925	1 987	932	2 126
Japan	1 121	15	1 107	459
China	3 435	264	489	0
Canada	1 676	1 404	173	358
South Korea	3 133	759	886	790
Brazil	296	85	83	1
India	402	1	16	248
Mexico	524	194	147	0
Russia	822	195	204	65
Australia	3 008	694	870	3 784
Switzerland	1 534	281	792	0
Turkey	643	526	195	330
Taiwan	1 273	410	340	0
Norway	1 454	472	405	0
Indonesia	548	86	51	176
South Africa	3	900	120	0
RoW Asia	316	101	77	57
RoW America	420	243	179	0
RoW Europe	44	192	129	265
RoW Africa	196	41	46	16
RoW Middle East	1 225	523	322	20

Appendix E

Table E.1: Ten largest emissions embedded in inputs consumed in each sector

Construction work			
Regional source	Inputs	Kt of CO2-eq	Share
China	Cement, lime and plaster	1 164 624	15%
	Electricity by coal	1 022 277	13%
	Basic iron and steel	480 421	6%
	Bituminous Coal	401 114	5%
	Non-metallic mineral products	259 107	3%
India	Cement, lime and plaster	142 397	2%
RoW Asia	Cement, lime and plaster	83 059	1%
India	Basic iron and steel	78 339	1%
China	Chemicals nec	75 116	1%
India	Bituminous Coal	70 917	1%
World	Rest of Sectors	4 159 042	52%
	Total	7 936 413	

Public administration and defence services			
Regional source	Inputs	Kt of CO2-eq	Share
United States	Electricity by coal	116 704	6%
China	Electricity by coal	103 457	6%
United States	Public administration	59 406	3%
	Electricity by gas	49 512	3%
China	Public administration	49 247	3%
	Steam and hot water supply	36 075	2%
RoW Middle East	Electricity by gas	29 303	2%
United States	Air transport services	28 528	2%
	Steam and hot water supply	26 895	1%
RoW Middle East	Electricity by petroleum	26 810	1%
World	Rest of Sectors	1 326 918	72%
	Total	1 852 857	

Health and social work services			
Regional source	Inputs	Kt of CO2-eq	Share
China	Chemicals nec	193 668	11%
	Health and social work	94 979	5%
	Electricity by coal	87 777	5%
United States	Electricity by coal	67 357	4%
China	Basic iron and steel	32 206	2%
United States	Electricity by gas	28 575	2%
RoW Middle East	Crude petroleum extraction	24 092	1%
Japan	Health and social work	23 173	1%
United States	Health and social work	22 037	1%
RoW Middle East	Electricity by gas	18 394	1%
World	Rest of Sectors	1 205 839	67%
	Total	1 798 099	

Electricity by coal			
Regional source	Inputs	Kt of CO2-eq	Share
United States	Electricity by coal	688 592	46%
India	Electricity by coal	308 693	21%
Australia	Electricity by coal	89 367	6%
Japan	Electricity by coal	54 846	4%
RoW Asia	Electricity by coal	49 989	3%
Indonesia	Electricity by coal	45 983	3%
Germany	Electricity by coal	37 552	3%
South Korea	Electricity by coal	36 996	2%
Turkey	Electricity by coal	26 388	2%
RoW Europe	Electricity by coal	19 202	1%
World	Rest of Sectors	144 243	10%
	Total	1 501 852	

Note: the final row 'Total' below each sector, gives their respective aggregate footprint (as in Table 5.1), whereas the columns named 'Share' give each input as a percentage of total footprint.