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Thesis for the degree of Philosophiae Doctor

Trondheim, November 2018

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Preface

This thesis has been submitted to the Faculty of Engineering (IV) at the Norwegian University of Science and Technology (NTNU) as a partial fulfilment of the requirements for the degree of Philosophiae Doctor. The work was carried out at the Industrial Ecology Programme (IndEcol), Department of Energy and Process Engineering (EPT), under the supervision of Prof. Richard Wood and co-supervision of Prof. Edgar G. Hertwich and Dr. Kirsten S. Wiebe. The work on this thesis was partially funded by the following European Union's seventh framework programme projects: PROSUITE (Development and Application of Standardized Methodology for the Prospective Sustainability Assessment of Technologies, contract 227078), CREEA (Compiling and Refining Environmental and Economic Accounts, contract 265134), DESIRE (Development of a System of Indicators for a Resource Efficient Europe, contract 308552) and Carbon-CAP (Carbon Emission Mitigation by Consumption-Based Accounting and Policy, (contract 603386), and by the project Eliod (Environmental and Labour Accounts for an OECD-based ICIO), commissioned by the Joint Research Centre of the European Commission.

Contents

Abstract

As the economy has become more globalized, labour and environmental impacts have been redistributed throughout the globe. Today, the complexity and fragmentation of global value chains mean that the distance between production and consumption has become longer, and consumers are often not aware of the volume or location of the upstream impacts of goods and services. Within the past decade, the use of input-output models allied to bilateral trade data have been increasingly used to assess environmental pressures embodied in traded trade. Recent developments on building harmonized time series of multi-regional input-output databases have improved the potential to do analysis of the global economy.

Here, I aim to lay out an analysis of the social and environmental dimensions of global value chains. In special, I focus on how trade and outsourcing affect labour worldwide. Low-cost labour has been one of the main factors for the increased level of outsourcing. Outsourced production comprise mainly manufacturing processes with high labour intensity and, often, stages in the production chain with high resource and energy use. While this increased labour generates positive impacts by creating jobs and generating income, especially in developing countries, it also generates undesirable social impacts and environmental externalities.

The backbone of this thesis are a set of harmonized labour accounts developed for the multi-regional input-output database EXIOBASE. This dataset allowed the analysis of socioeconomic and environmental impacts and pressures brought by the fragmentation of production chains in a single framework. In this thesis, I present two articles that describe the creation of this dataset and five articles that analysed different socioeconomic and environmental aspects of global value chains.

We perform an analysis of productivity changes for labour, energy and greenhouse gas emissions when internalizing trade. We show that labour-intensive countries with lower labour costs also have lower energy and carbon productivities compared to developed economies, and show that the relocation of labour-intensive production stages to lower-income countries can lead to higher overall environmental pressures. The evolution of how labour and carbon are distributed in global value chains is further explored through an analysis over time where we show that, for developed regions, outsourcing and changes in trading partners have contributed to changes in labour and carbon footprints, while both labour and carbon footprint in developing regions were mainly driven by their own increased domestic consumption. In

addition, we show how environmental footprints are strongly coupled to the countries' affluence, and the decoupling of environmental pressures embodied in consumption from economic development present a much higher challenge that goes beyond improving domestic technology. The challenge for meeting social development while reducing global environmental pressures require multilateral efforts that combine consumers and producers in global value chains.

However, any changes in the production structure in a globalized economy, for example, driven by multilateral environmental policies such as climate agreements, can affect workers all around the world. We show that there are large volumes of labour embodied in global value chains. Furthermore, there are differences in labour conditions and composition between developing and developed regions. We quantify undesirable labour conditions associated with international trade, and show that high-income countries can double their 'bad labour' footprints when accounting for imports from less developed regions. The undesirable labour conditions we quantify are occupational health damage, vulnerable employment, gender inequality, incidence of unskilled and low-skilled workers, child labour, and forced labour. While any social impact of global value chains, negative or positive, driven by consumption, both consumers and producers benefit from trade. The reduction of undesirable labour conditions and improving the resilience of low-income workers in periods of economic stagnation or recession are of crucial importance for attaining the sustainable development goals of decent work. We show that low-skilled workers and workers in self-employment in the supply chain of traded goods are more vulnerable to economic downturns. During economic crisis, such as the one experienced in 2008/09, reduced consumption led to a decline in trade, which in turn resulted in loss of employment and income worldwide. However, reduced consumption in developed economies affected workers in developing economies the most.

Understanding the links between employment and income in global value chains gives us the opportunity to improve international cooperation to reduce environmental pressures in global value chains, while at the same time maintaining the economic benefits required to fulfil human needs and reduce global inequalities. This thesis aims to contribute to such efforts.

Acknowledgments

First of all, I would like to thank my supervisor, Richard Wood, and my co-supervisors, Edgar Hertwich and Kirsten Wiebe. Richard, thank you for the trust you have placed in me. You pushed me to do better, to be creative, and to be independent. Even when I felt lost, you made me regain confidence on my work, and you always kept your door open to me whenever I needed. Edgar, thank you for your support on my early years in IndEcol, and for the several hours of great discussions that forced me to see the big picture and think outside the box. And thank you, Kirsten, for hours and hours of discussions, laughs, coffees, skiing, cabin trips and drawing equations on white boards. You pressed me to go beyond my industrial ecology comfortable zone and convinced me to dig deeper into the economics literature.

I would like to thank all my co-authors for their work and contribution to this thesis. Thank you, Tommy Wiedmann, for receiving me in Australia when I needed summer in the middle of Norwegian winter. And of course, I would like to thank my colleagues, my fellow indecolers. You made me enjoy my time in the office and made me look forward to come to work even when I was on the most stressful moments. Thank you for the discussions, whether work-related or not, that took place on the corridors, meeting rooms, green couches, lunch breaks, over cake Fridays and wine lotteries, and especially, around the coffee machine. Thank you for the cabin trips, hiking, skiing, berry picking, climbing, parties, horseback riding, swimming, mini-golfing and for your friendship. You are all an essential part of my life in Trondheim, and it would not be the same without you in it.

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Finally, thank you, Vegar. I would not be able to do this without you.

List of publications

This thesis is based on the seven articles listed as “Primary publications” in the list below, all for which I was lead author. The seven publications are appended to this thesis and represent the scientific contribution of my work. Articles 1, 3, 6 and 7 have been published in academic journals, while the remaining have not yet been submitted to any journal by the time this thesis was printed. A copy of articles 1-7 can be found in Appendices A-G at the back of the thesis, together with supporting information where applicable and not available online. The order of the articles in the primary publications list follows the order they appear in section 3. Other publications I co-authored throughout my doctoral work are also listed (8-24), but are not appended to nor used as basis for this thesis.

Primary publications

1. Simas, M., K. Stadler and R. Wood. 2018a. EXIOBASE 3 - Supporting Information for labor accounts (S7). Supporting information for: Stadler, K. *et al.* 2018. EXIOBASE 3: Developing a time series of detailed Environmentally Extended Multi-Regional Input-Output tables. *Journal of Industrial Ecology* 22(3): 502-515.
Author contribution: research design, data collection and writing.

2. Simas, M., K. Wiebe and R. Wood. 2018b. Mapping the structure of the global labour market: Developing fully harmonized labour accounts for MRIO analysis. *Unsubmitted manuscript.*
Author contribution: research design, modelling and writing.

3. Simas, M., R. Wood, and E. Hertwich. 2015. Labor Embodied in Trade: The Role of Labor and Energy Productivity and Implications for Greenhouse Gas Emissions. *Journal of Industrial Ecology* 19(3): 343–356.
Author contribution: research co-design, data collection, modelling, analysis, visualization and writing.

4. Simas, M., E. Hertwich and R. Wood. 2018c. Drivers of employment and carbon emissions in global value chains. *Unsubmitted manuscript.*
Author contribution: research co-design, modelling, analysis, visualization and writing.

5. Simas, M., S. Pauliuk, R. Wood, E.G. Hertwich, and K. Stadler. 2017. Correlation between production and consumption-based environmental indicators: The link to affluence

and the effect on ranking environmental performance of countries. *Ecological Indicators* 76: 317–323.
Author contribution: research co-design, analysis, visualization and writing.

6. Simas, M., K. Wiebe and R. Wood 2018d. Jobs in global value chains: Employment and wages in European production and consumption. *Unsubmitted manuscript.*
Author contribution: research idea and design, modelling, analysis, visualization and writing.

7. Simas, M., L. Golsteijn, M. Huijbregts, R. Wood, and E. Hertwich. 2014. The "Bad Labor" Footprint: Quantifying the Social Impacts of Globalization. *Sustainability* 6(11): 7514–7540.
Author contribution: research co-design, data collection, modelling, analysis, visualization and writing.

Additional publications

8. Wood, R., K. Stadler, T. Bulavskaya, S. Lutter, S. Giljum, A. de Koning, J. Kuenen, H. Schütz. J. Acosta-Fernández, A. Usubiaga, M. Simas, O. Ivanova, J. Weinzettel, J.H. Schmidt, S. Merciai and A. Tukker, 2015. Global Sustainability Accounting—Developing EXIOBASE for Multi-Regional Footprint Analysis. *Sustainability* 7(1): 138–163.
9. Tukker, A., T. Bulavskaya, S. Giljum, A. de Koning, S. Lutter, M. Simas, K. Stadler and R. Wood. 2016. Environmental and resource footprints in a global context: Europe's structural deficit in resource endowments. *Global Environmental Change* 40: 171–181.
10. Stadler, K., R. Wood, T. Bulavskaya, C.J. Södersten, M. Simas, S. Schmidt, A. Usubiaga, J. Acosta-Fernández, J. Kuenen, M. Bruckner, S. Giljum, S. Lutter, S. Merciai, J.H. Schmidt, M.C. Theurl, C. Plutzar, T. Kastner, N. Eisenmenger, K.H. Erb, A. de Koning and A. Tukker. 2018. EXIOBASE 3: Developing a time series of detailed Environmentally Extended Multi-Regional Input-Output tables. *Journal of Industrial Ecology* 22(3): 502-515.
11. Wood, R., K. Stadler, M. Simas, T. Bulavskaya, S. Giljum, S. Lutter and A. Tukker. 2018. Growth in Environmental Footprints and Environmental Impacts Embodied in Trade: Resource Efficiency Indicators from EXIOBASE3. *Journal of Industrial Ecology* 22(3): 553–564.
12. Schmidt, S., C.J. Södersten, K. Wiebe, M. Simas, V. Palm and R. Wood. Understanding greenhouse gas emissions from Swedish consumption – Current challenges in reaching the generational goal. *In Review in Journal of Cleaner Production* (2018).

13. Montt, G., K.S. Wiebe, M. Harsdorff, M. Simas, A. Bonnet and R. Wood. Does climate action destroy jobs? An assessment of the employment implications of the 2-degree goal. *In Review in International Labour Review* (2018).

14. Wiebe, K.S., M. Harsdorff, G. Montt, M. Simas and R. Wood. A global circular economy scenario in a multi-regional input-output framework 2030. *In Review in Resources, Conservation & Recycling* (2018).

15. Weidema, B., M. Simas, J. Schmidt, M. Pizzol, S. Løkke, and P. Brancoli. Relevance of attributional and consequential information for environmental product declarations. *In Review in The International Journal of Life Cycle Assessment* (2018).

Book chapters

16. Simas, M. and R. Wood. 2015. The Bad Labour Footprints: Linking Local Labour Conditions to Global Supply Chains. In The Sustainability Practitioner's Guide to Social Analysis and Assessment, ed. by Joy Murray, Darian McBain, and Thomas Wiedmann, 118–129. Champaign, IL: Common Ground Publishing.

17. Simas, M. and R. Wood. 2018. The distribution of labor and wages embodied in European consumption. In The Social Effects of Global Trade: An Analysis of Benefits and Costs, ed. by Joy Murray, Arunima Malik, and Arne Geschke. Pan Stanford.

Contribution to reports

18. Tukker, A., T. Bulavskaya, S. Giljum, A. de Koning, S. Lutter, M. Simas, K. Stadler, and R. Wood. 2014. The Global Resource Footprint of Nations: Carbon, water, land and materials embodied in trade and final consumption calculated with EXIOBASE 2.1. Leiden/Delft/Vienna/Trondheim: The Netherlands Organisation for Applied Scientific Research; Leiden University; Vienna University of Economics and Business; Norwegian University of Science and Technology.

19. Wiebe, K., M. Simas and R. Wood. Contribution to: International Labour Organization, 2018. Greening with jobs – World Employment Social Outlook 2018. Chapter 2: Employment and the role of workers and employers in a green economy.

Project deliverables

20. CREEA Deliverable D8.3: Case reports on carbon and land use, 2014. Wood, R., M. Simas, K. Stadler, E. Hertwich, A. Tukker, T. Bulavskaya, U. Temurshoev.

21. DESIRE Deliverable D5.3: Integrated report on EE IO related macro resource indicator time series, Annex – Labour, 2015. Simas, M.

22. DESIRE Deliverable D9.2: Report on structural analysis of drivers, 2015. Wood, R., K. Stadler, M. Simas, C.J. Södersten.

23. Carbon-CAP Deliverable D4.4: Global drivers of change in carbon emissions from a consumption perspective, 2016. Simas, M., R. Wood, S. Linder.

24. Eliod Technical Report: ELIOD – Environmental and Labour Accounts for an OECD-based ICIO, 2017. Wood, R., K.S. Wiebe, M. Simas, S.Y. Schmidt, J. Kuenen.

1. Introduction

Humanity's substantial pressures on natural resources during the past decades has led to such important impacts on the Earth system that it has been referred to as a new geological epoch, the Anthropocene[1]. The use of natural resources by humans, comprising its extraction, processing, use and discard, has changed dramatically due to factors such as population and economic growth, urbanization, industrialization, and rising consumption, especially from the mid-20th century[2]. These changes have led to a rapid reshaping of the volume and composition of environmental inputs to the human production and consumption systems – the human economy – and the outputs, in form of waste, back to the environment. As a result, environmental impacts have increased in magnitude and scale, such as the depletion of large areas of the ozone layer[3,4], global climate change[5], and global changes in the biosphere[6,7]. In order to mitigate these impacts, we must understand the underlying societal drivers for the growth in resource use.

Environmental impacts are intrinsically linked to the material basis of production and consumption systems. For example, the production of biomass generates pressure on land use and causes land use changes. Global demand for food, feed and fuel is a major driver for the expansion of cropland and pastures in the developing world – between 1980 and 2000, over 80% of new agricultural land in the tropics was developed in place of pre-existing forests, most of it over intact primary forests[8]. Agriculture also drives around 90% of all freshwater consumption worldwide[9], and fertilizers and pesticides runoff (together with municipal and industrial discharges) can impact freshwater and marine ecosystems through aquatic nutrient eutrophication[10,11]. Mining of minerals for manufacturing and construction lead to land use pressures[12,13], and the processing of minerals and ores into metals and non-metallic minerals such as cement have high direct and indirect greenhouse gas (GHG) emissions[14]. The drivers of these environmental pressures are not only linked to our increasing consumer demand, but also the way we produce goods and services. The use of cheap foreign labour, the increasing automation of production and the lack of valuation of environmental externalities has led to unregulated social and environmental impacts in the supply chains of consumed goods and services, including of some of the most basic needs of human societies such as food and shelter. Our production and consumption systems have put us beyond or, at least, at risk of exceeding a "safe operating space" in at least four of nine planetary boundaries[15,16], threatening the balance of the Earth biological and geochemical systems.

It becomes, thus, paramount to shift from an economy that aims to maximize production and consumption to an economy that aims to fulfil human needs within the planetary boundaries[17]. A framework to address human needs are represented in the United States Sustainable Development Goals (SDG), with 17 goals covering social, economic and environmental aspects of human systems[18]. Looking at the goals, it becomes obvious the challenge to design a system that will allow billions of people to rise from poverty and improve their livelihood, reduce global and local inequalities, allow for economic growth and industrial development, and at the same time, reduce human pressure on the environment. Within this framework, Raworth (2017)[19] introduces the concept of a "safe and just space for humanity", which would situate in an area that lies above the minimum threshold for the social foundation of society, but below Earth's planetary boundaries, illustrated in Figure 1. O'Neill and colleagues (2018)[17] downscaled the planetary boundaries to national *quotas* for assigning equal shares of planetary boundaries per capita, and assessed how 150 different countries would meet their social thresholds compared to their environmental footprints, finding that no country meets the minimum social threshold at environmentally sustainable levels.

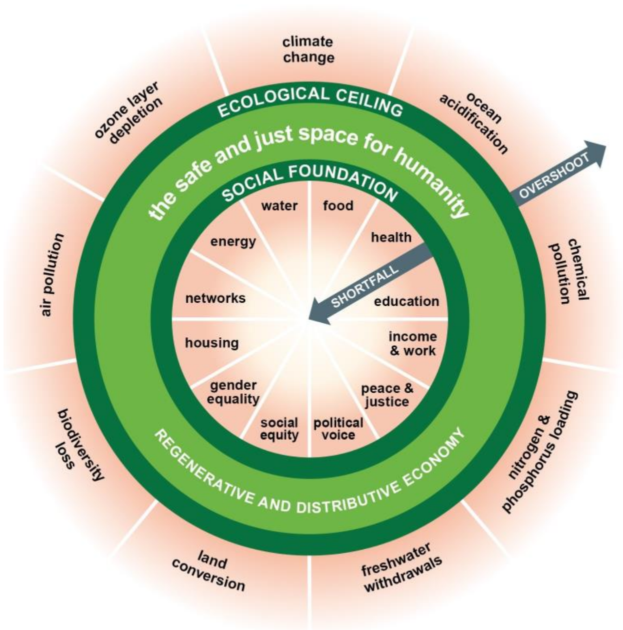

Figure 1. The "Doughnut" of social and environmental boundaries, from Raworth (2017)[19]. The green area represents the "safe and just" space for humanity, where minimum social thresholds would be met within planetary biophysical boundaries. The area below the limits of this space represents shortfall of social indicators, where the minimum social thresholds are not met. The area above the limits of this space represents ecological overshoot, where environmental pressures would push planetary boundaries beyond their limits.

Centre of Raworth's discussion is the need to look beyond economic growth, and some authors point in the direction of a need for no-growth or even degrowth[20,21]. However, in a world where population growth is expected to increase in over 3 billion people towards the end of the century[22] and where a large share of the population lives in poverty and lacks decent work and living conditions, it is hard to imagine that we would be able to meet social development goals and limit economic activity. Economic growth is often considered essential to generate additional employment and income, and consequently, improve living conditions, especially in developing countries with high unemployment and underemployment rates. While scenarios of cleaner technology adoptions estimate that job losses would be compensated with job creation[23,24], there are still trade-offs between employment and mitigation of environmental pressures. In a network of increasingly globalized supply chains, any changes in production structures will lead to potentially very different effects across regions, affecting (positively or negatively) labour and income around the world. The demand for higher deployment of renewable energy technologies over fossil fuel, for example, would lead to loss of jobs and income in coal mining-oriented locations, while increasing the demand for jobs and creating income in other sectors, such as mining for ores, production of electric and electronic components, construction, among others[25]. However, these jobs losses and creation would happen in different parts of the world, and the volume and location of them depends not only where the technology – wind turbines or fuel – is being produced, but from where inputs are being sourced. In order to quantify the overall environmental pressures and social impacts from changes in production and consumption, we need to take into account the fragmented nature of global value chains (GVCs) and how resources and labour have been distributed over time.

1.1. Global value chains, employment and environmental leakage

Throughout the developing world, there has been a shift in policies related to GVCs, moving from a development strategy of import-substituting industrialisation focused on the domestic market to export-oriented production[26]. With increasing trade liberalisation, emerging economies increased their share in total global exports. Advances in information, communication and transport technology led to the fragmentation of production chains, where different tasks performed in the production process are spread across different countries[27,28]. Value chains have become more global, increasing the fragmentation of production outside regional blocks[29].

Since the second half of the 20th century, most developed economies have observed a persistent decline in manufacturing jobs, especially those low in research and development (R&D), and increased participation of services in the gross domestic product (GDP) and in the labour force[30]. Manufacturing activities in developed economies further specialized in more complex exports[31]. This fragmentation of tasks, leading to a new 'global division of labour', is characterized by production specialization – not in different products, but in different production stages[32] and outsourcing of labour-intensive production stages to low-cost labour-abundant countries[33]. In this new fragmented production process, resource use, labour, payment of wages, creation of value added (VA) and, finally, final consumption, are spread between regions. Mudambi (2008)[34] points to the geographical location of the value chain disaggregation of knowledge-intensive industries in what the author calls the 'smile curve', shown in Figure 2. The author examines the distribution of stages which create intangible assets[35], which represents production processes that create high VA based on specialized activities. These intangible assets are services provided by R&D, design and creative processes, on the left side of the figure, and by marketing and sales services on the right side. In the middle of the production process lies the actual manufacturing stages, based on repetitive process and mass production. These middle processes are often the most labour-intensive stages and require a lower share of high-skilled workers to perform. These stages are also characterized by higher consumption of natural resources and higher environmental pressures. Under the current location pattern of GVCs, the production stages with higher VA are largely performed in developed countries, while activities that add lower value are outsourced to emerging economies[26,34] [a].

[a] The author also notes that while this is the current geography of GVCs, this is not a static pattern. Firms from developing countries are creating competence in the production of intangible assets (in the figure, '*catch-up*') at a fast rate, while standardized parts of the high value added activities are being relocated to developing economies (in the figure, '*spillover*'). This definition of spillover is not the same as used in this thesis. Spillover, here, are positive or negative effects that one industry generates in the rest of the economy due to demand of inputs and creation of knowledge and innovation.

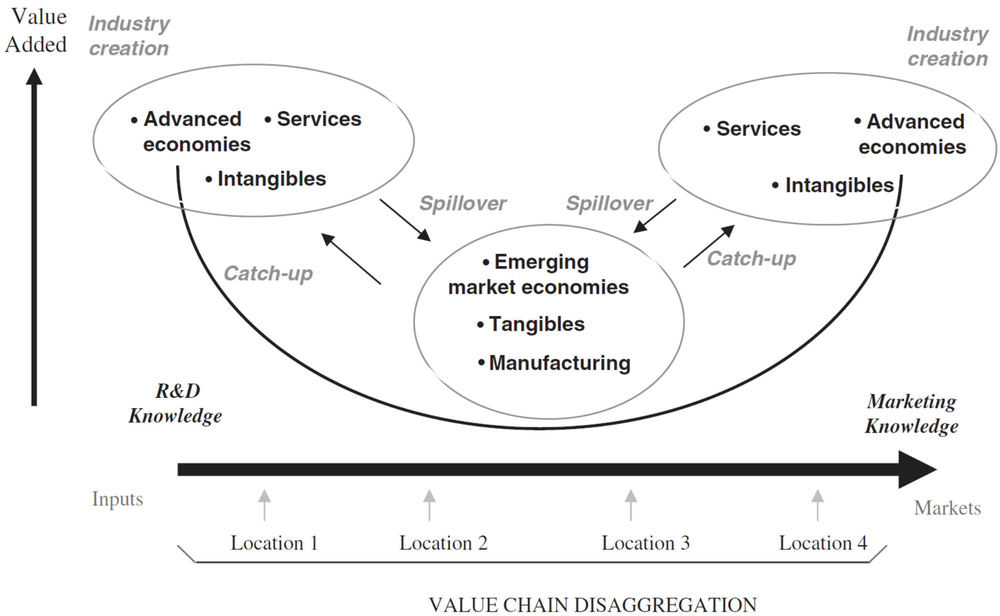

Figure 2. The smile-dynamic analysis, from Mudambi (2008)[34].

The increased international sourcing and offshoring generate important economic benefits to developing economies. Trade openness and increased exports have been considered as a strategy for economic growth and development, especially for developing economies[26,36–39]. Many developing countries specialize in labour-intensive manufacturing and/or in resource-intensive production. While the increased participation in exports allows for economic growth and job creation, it has the question whether the search for lower labour costs could generate a 'race to the bottom' regarding labour standards in order to maintain competitiveness[40]. As many outsourced stages are often resource-intensive, it has also raises concerns about ecologically unequal exchange, in which resources are extracted from resource-rich, mostly poorer, economies to satisfy consumers in wealthy countries[41,42]. Although exports from resource-rich economies would naturally be resource-intensive due to comparative advantages and resource endowments[43,44], it poses a problem when environmental externalities are not priced and they happen in disproportionate volume compared to their economic gains[45,46].

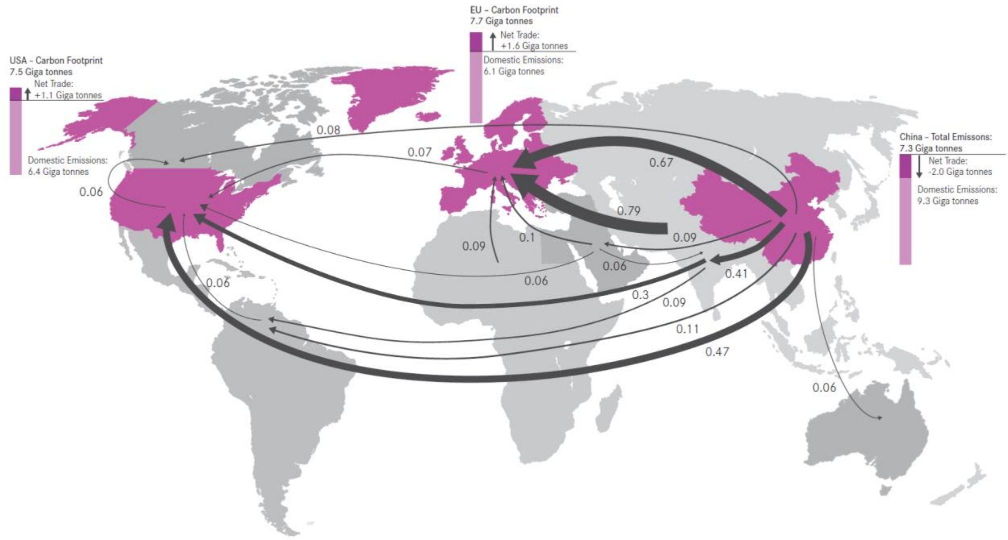

Figure 3. Net flows of GHG emissions embodied in traded goods, with China (main net exporter), Europe and the United States (main net importers) highlighted. The origin of emissions in the map represent where emissions are happening, and the destination represents the regions where final products are consumed. From Tukker et al. (2014)[52].

The fragmentation of production chains has raised the concern on shifts on the regional distribution of GHG emissions through trade[47]. The issue of carbon emissions, like ozone-depleting compounds, is that it is a global pollutant. Therefore, the effect is the same regardless where in the world the emissions are happening. Outsourcing processes have displaced carbon emissions from high-income to low-income countries[48]. This carbon displacement led to some developed economies, such as Germany and the United Kingdom, being able to meet their territorial GHG emissions reduction targets under the Kyoto Protocol at the expense of increased emissions elsewhere[49]. Between 1995 and 2008, approximately 15% of the additions to global carbon emissions were emitted in developing countries but driven by consumption in high-income regions[50]. Emissions embodied in traded goods[b] grew rapidly between 2000 and

[b] Emissions embodied in traded goods or in consumption are not physically a part of the goods, but were emitted in the upstream supply chain of the production of goods and services. For example, a scenario where iron ore is extracted in Brazil, processed into steel in China, and exported to Germany to produce a wind turbine sold to the Italy, the emissions, jobs, and other pressures and impacts happening in the production stages in Brazil, China and Germany are 'embodied' in the wind turbine purchased in Italy.

2007, especially due to the increased participation of China in global exports[51]. In 2007, around 30% of Chinese CO_2-eq emissions were associated with exported products, and most of these emissions were embodied in final products consumed in Europe and the United States[51,52], as shown in Figure 3. This outsourcing of environmental burdens also applies to other environmental pressures. Between 1995 and 2011, the share of global materials, water, energy and land use embodied in traded goods also increased, and most of it was associated with trade flows from developing to developed economies[53].

Global climate agreements and negotiations do not yet take into consideration the interconnectedness of the national economies into a global production network. There are many challenges to do so, and they are beyond the scope of this thesis. However, policy-makers on local and regional levels have begun accounting for the effects of international sourcing on resource use[54,55]. The allocation of pressures and impacts[c] happening in the upstream supply chain to final products is called consumption-based accounting, widely known in the industrial ecology field as footprinting.

1.2. Consumption-based accounting: linking global value chains to consumption

Consumption-based (CB) accounting, or footprints, accounts for pressures or impacts, such as labour and CO_2 emissions, at the point of consumption of a final good or service. It is computed by adding up all the pressures happening in the entire production chain to the final goods and services purchased in a country by households, governments, or used to build capital such as infrastructure. Footprints complement the production-based (PB) accounts by providing an understanding of which products purchased by final consumers in different countries are

[c] Throughout this thesis, I distinguish between social and economic *impacts*, and environmental *pressures*. In economics, impacts can be defined as the effects on the level of economic activity in an area, and can be measured in indicators such as economic output, value added, wealth, income and jobs [56]. In environmental sciences, the definition of pressures and impacts follows the DPSIR framework: Driver-Pressure-State-Impact-Response. For example, the burning of fossil fuels (driver) generates carbon emissions (pressure), which in turn increase the average temperature of the Earth (state), leading to reduced agricultural yield, health problems, and destruction of coastal ecosystems (impact), which in turn leads to climate policy to mitigate emissions (response) [57]. Therefore, I refer to *pressures* when describing environmental indicators and *impacts* when describing social and economic indicators.

driving the demand for production – and therefore, emissions, labour and other pressures and impacts – in other regions.

Footprints are useful in different ways. First, it can identify what are the main lifestyles drivers for environmental pressures. The ecological footprint was one of the first concepts created to allocate the impacts of lifestyles to an indicator – areas of land needed to supply humanity with all resources and to absorb all annual waste and carbon emissions[58,59], and has been widely used for sustainability assessments (e.g. [60–62]), despite its criticisms[63–65]. More recently, footprints for separate environmental indicators such as for carbon and water have become more popular. These footprints identify hotspots of goods and services purchased by individuals or households that drive high environmental pressure. In this way, people can change their consumption patterns in order to reduce their personal impact[66–68] and policy-makers can focus on regional or local measures to find better mitigation alternatives[69–71].

A second application for CB accounts is to identify source and destination of economic, social and environmental impacts and pressures in GVCs. A first conclusion from this application is that the level of consumption is a strong variable to explain national environmental footprints[72–74]. Within this framework, PB accounts include impacts embodied in all production from domestic industries, both to be consumed domestically and for exports. CB, on the other hand, includes impacts embodied in all production, regardless of where it happens, to domestic consumption. The difference between PB and CB would be that the latter excludes impacts embodied in exports, and includes impacts embodied in imports. Footprints of international trade link local social, economic and environmental impacts and pressures to final consumers through traded goods. The recent advances on developing global multi-regional input-output (MRIO) databases with a range of social and environmental extensions has boosted the study of the social and environmental impacts and pressures of traded goods[75,76]. These databases provided the required tools to link production and consumption in GVCs with growing production fragmentation.

1.3. Research questions

During the past two decades, a growing number of indicators have been studied through the framework of GVCs and footprints of international trade: economic measures as value added[29,77–80], wages and labour[81–88]; environmental indicators such as GHG emissions[48,49,72,89–93], water[74,94,95], land[13,73,96,97], materials[98–101], and biodiversity[102–104]; and social impacts such as occupational health[105], inequality[106], and child labour[107,108]. A considerable number of studies on this subject – including most of the social footprints of trade and the links between labour and consumption in GVCs – were published in the last five years. My work summarized and appended to this thesis has contributed to these two latter topics.

With this thesis, I aimed to contribute to the analysis of social and environmental dimensions of trade by exploring how global value chains have shaped the distribution of labour and environmental pressures worldwide and, especially, how this distribution has changed over time. The main research question asked in this thesis was:

What have been the social and environmental consequences of the changes in global value chains and how have they shifted in the past decades?

I answer this research question through a series of sub-questions, each of them addressed in different ways by the primary publications in this thesis:

Q1. How have global value chains changed the origin and intensity of labour, energy, and carbon emissions embodied in the flows of goods and services sourced internationally?

Countries have different resource productivity, and the intensity of impacts and pressures depend on how efficiently a country uses its resources (capital, labour, energy sources) to produce goods and services, and on the volume of goods and services produced. My hypothesis for this question was that, due to increased international sourcing from labour-intensive developing countries, more employment happening in developing economies would be embodied in internationally traded goods. At the same time, this would result in a higher share of energy and carbon embodied in trade originating from developing economies. Due to lower labour and energy productivities as well as a higher carbon intensity of energy use in developing countries, I expected that the volume of labour and greenhouse gas emissions embodied in trade would have increased faster than monetary trade.

Q2. What are the social impacts associated to the distribution of employment in global value chains?

The higher participation of developing economies in global exports, especially since the early 2000s, has led to positive aspects such as job creation and income, and an increasing number of jobs are associated with international trade. However, it is important to take into account the types of jobs created, as lower labour costs could start a 'race to the bottom' regarding labour standards in order to maintain competitiveness [40]. My hypothesis was that, as labour conditions in developing economies are usually worse than in developed countries, the increased sourcing from lower-income countries would distribute these social impacts among global value chains, resulting in higher social footprints of higher-income countries when accounting for these imports.

Q3. What are the trade-offs between socioeconomic benefits and environmental pressures in global value chains?

Production activities generate environmental pressures, but they also create economic benefits such as income and other value added and jobs. My hypothesis was that, on one hand, countries who import benefit from lower costs of production and decreased territorial environmental pressures. On the other hand, countries who export benefit from the creation of jobs and value added, but resource use and environmental pressures are higher than those used to satisfy their own domestic consumption. In addition, decreased consumption, especially from developed economies, is needed to decrease environmental pressures, but they might also affect jobs and income, especially those in lower-income countries.

1.4. Thesis structure

This thesis is structured in four main chapters. Chapter 1 establishes the background and motivation to the research, and presents the main research question and sub-questions of the thesis. Chapter 2 describes the methodological framework of MRIO and presents the database that constitutes the basis for the articles, EXIOBASE. The methodology presented in Chapter 2 form the basis for the work in each of the articles in this thesis. However, the reader should consult each article and its supplementary information (when applicable) to read about specific methods and data sources. In Chapter 3, I summarize the articles in the thesis. Chapter 3 is divided into the description of the dataset development (section 3.1) and in analysis of the data (section 3.2). In Chapter 4, I discuss the findings and overall contribution of the thesis, and present a discussion on limitations of the analysis. Finally, chapter 5 lays out the conclusions and outlook from this thesis.

2. General methodological approach

2.1. Environmentally-extended multi-regional input-output analysis

Input-output analysis (IOA) is an accounting framework developed by Wassily Leontief in in the 1930's[109], where he described the economy as a circular flow. The IOA framework represents the economic transactions of a given year in a tabular form, describing intermediate trade between industries, the use of factors of production (labour, capital and land), and the purchase of final products by consumers. This framework establishes the structure of the economy in an interlinked network, where the demand for goods or services from one industry leads to impacts and spillovers in other economic sectors. As described by Leontief (1974, p.387)[110], "*Direct interdependence between two processes arises whenever the output of one becomes an input of the other: coal, the output of the coal mining industry, is an input of the electric power generating sector. The chemical industry uses coal not only directly as a raw material but also indirectly in the form of electrical power*". In the post-war period, Leontief included two other aspects to his economic framework: the assessment of environmental pollution[111] and international trade and the structure of the world economy[110,112]. The development of this framework led Leontief to win the Nobel Prize in Economics in 1973, and IOA has become one of the most applied methods in economics[113].

Due to the high demand of data and computing capacity, it was only in recent years that fully integrated multi-regional input-output (MRIO) were developed[75,114], showing the interconnectedness of the global economy. This section sets out the general mathematical framework of MRIO and the extended analysis to study social and environmental impacts and pressures in GVCs, and describes the MRIO database used in the articles in this thesis.

2.1.1. Fundamentals of EE-MRIO mathematical modelling

The starting point for input-output models are the economic supply and use tables (SUT), compiled by statistical offices. Supply tables describe all products[d] supplied by all industries

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[d] Note that products comprise all goods and services, and not only physical goods.

in a region and products supplied to the market by imports. Use tables describe all products used by industries in the region, as well as products used by final consumers and gross value added (GVA) generated by industries. By combining the two tables one can obtain an input-output table (IOT), which describe the region's economy through five main components: a square intermediate demand matrix **Z**, a vector of total output **x**, a square technical coefficients matrix **A**, a final demand matrix **Y**, and a GVA matrix **V**[e].

The intermediate demand matrix **Z** records the flows of products between all n industries in the economy. This matrix has dimension $n \times n$, and each element z_{ij} represents the total purchase of products from industry i as inputs to production of industry j (eq. 1). The **Z** matrix shows each industry j described in the IOT as producer (z_j^P) and consumer (z_j^C):

$$\mathbf{Z} = \begin{bmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{n1} & \cdots & z_{nn} \end{bmatrix} \tag{1}$$

$$z_j^P = \sum_{i=1}^{n} z_{ji} \ ; \ z_j^C = \sum_{i=1}^{n} z_{ij} \tag{2}$$

The total output vector **x** describes all outputs of the n industries in the IOT, and has dimension $n \times 1$. Each element x_j represents the sum of all production of industry j that is supplied to other industries (z_j^P), as well as all production from industry j that is purchased by final consumers and exported to other regions outside the IOT boundary. Matrix **Z** and vector **x** are represented in monetary units[f], for example, euros (€).

The technical coefficient matrix **A** shows the requirements of inputs from other industries to produce one unit of output in each industry. It has dimension $n \times n$, and each element a_{ij} represents requirements from each industry i to produce one unit output of industry j, and is

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[e] In this section I follow standard algebra notation: bold uppercase variable names (**A**) represent matrixes; bold lowercase variable names (**x**) represent vectors; and italic lowercase represent scalars (z_{ij}) and indexes (j).

[f] Except in mixed units or in physical IOT, which is not the case in this thesis. Here, IOTs are always considered to be only in monetary units.

represented in monetary units per monetary units (in this case, €/€). In the equations below, $\widehat{}$ denotes a diagonalised vector.

$$\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1} \tag{3}$$

The final demand matrix **Y** shows the total demand of goods and services by all f final consumers, and has dimension $n \times f$. It is described in total monetary units (€). Final demand is usually comprised of consumption by households, government expenditure, consumption of products for gross capital formation, changes in inventories, and exports.

The GVA matrix **V** describes all GVA created by each industry. GVA are non-industrial inputs to production and can be described in g different categories, such as taxes, subsidies, wages and other compensation to workers, consumption of fixed capital and profits to shareholders. It has the dimension $g \times n$.

One of the main characteristics of an IOT are that inputs are balanced to outputs. In this case, the inputs (eq. 4) to industry j from other industries and inputs of GVA must equal outputs (eq. 5) from industry j to all industries and to final consumers. In the following equations, $'$ denotes a transposed vector and **i** is a vector of ones in the size of the matrix it is multiplying. The purpose of the **i** vector is to sum over the rows or columns to transform a matrix into a vector:

$$x_j = \sum_i z_{ij} + \sum_g v_{gj} \rightarrow \mathbf{x}' = \mathbf{iZ} + \mathbf{iV} \tag{4}$$

$$x_j = \sum_i z_{ji} + \sum_f y_{jf} \rightarrow \mathbf{x} = \mathbf{Zi} + \mathbf{Yi} \tag{5}$$

The main contribution of input-output analysis is to be able to associate the total production from industries to the final consumption of goods and services. By substituting eq. 3 in eq. 5, we can rewrite total output as being the product of direct requirements of industries to produce total output plus the supply to final demand ($\mathbf{y} = \mathbf{Yi}$). We can, then, calculate total output required from each industry as a function of final demand by using the Leontief inverse **L**. Below, **I** is an identity matrix comprised by a diagonal of ones ($\mathbf{I} = \hat{\mathbf{i}}$) the same size as **A**:

$$\mathbf{x} = \mathbf{Ax} + \mathbf{y} \tag{6}$$

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = \mathbf{L}\mathbf{y} \tag{7}$$

The Leontief inverse $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ has dimension $n \times n$, and it describes total requirements associated to one unit of final demand. Each element l_{ij} includes, in addition to the direct output from industry i to produce one unit of product j to final consumers ($a_{ij}y_j$, $y_j = 1$), all indirect output from industry i to satisfy the requirements from all industries in the upstream supply chain of y_j. Equation 7 holds for any final demand, and industry requirements can be modelled to any user-defined final demand vector $\mathbf{y}^*$.

Equation 6 describes output based on intermediate consumption and final demand, but does not distinguish imports and exports. It describes a closed system that does not trade with any other system, which is not the case for any economy in the world. We can then rewrite eq. 7 to include a vector of gross exports ($\mathbf{e}$) and a vector of gross imports ($\mathbf{m}$):

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} + \mathbf{e} - \mathbf{m} \tag{8}$$

To study the effects of global value chains, however, we need models that explicitly distinguish origin and destination of imports and exports. First, gross imports are decomposed in imports to intermediate industries and to final demand. Thus we have $\mathbf{Z} = \mathbf{Z}^d + \mathbf{Z}^m$ (and correspondingly, $\mathbf{A} = \mathbf{A}^d + \mathbf{A}^m$) and $\mathbf{Y} = \mathbf{Y}^d + \mathbf{Y}^m$. Superscripts d and m represent domestic and imports, respectively. The import matrices $\mathbf{Z}^m$ and $\mathbf{Y}^m$ represent all imports, but does not distinguish the origin of these imports. The next step is to decompose the import matrices in c different matrices, where c is the number of regions we describe in the MRIOT. Using data from bilateral trade statistics, we can split total imports between intermediate industries and final demand. Total bilateral trade from region r to region s can be described as gross exports $\mathbf{e}$ from region r to region s, and can be allocated to intermediate industries and to final demand[g]:

$$\mathbf{e}^{rs} = \mathbf{Z}^{rs}\boldsymbol{i} + \mathbf{Y}^{rs}\boldsymbol{i} \tag{9}$$

[g] The decomposition of gross exports into exports to intermediate and final demand can be done in different ways. Although this thesis does not expand on the different methods used for this distribution, the database used throughout the articles, EXIOBASE, assumes proportional shares of imports for each product, where the origin mix is the same in both imports to intermediate and final demand. For example, if gross imports of steel to country A were 20% from country B and 80% from country C, all demand for imported steel by all industries and final consumers would be composed by 20% from country B and 80% from country C.

Thus, we can describe imports to region s as:

$$\mathbf{m}^s = \sum_{r \neq s} \mathbf{e}^{rs} = \sum_{s \neq r} (\mathbf{Z}^{sr} + \mathbf{y}^{sr}) = \sum_{s \neq r} (\mathbf{A}^{sr}\mathbf{x}^r + \mathbf{y}^{sr}) \tag{10}$$

We can then expand the IOT to an MRIOT with c regions:

$$\begin{bmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \\ \vdots \\ \mathbf{x}^c \end{bmatrix} = \begin{bmatrix} \mathbf{A}^{11} & \mathbf{A}^{12} & \dots & \mathbf{A}^{1c} \\ \mathbf{A}^{21} & \mathbf{A}^{22} & \dots & \mathbf{A}^{2c} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}^{c1} & \mathbf{A}^{c2} & \dots & \mathbf{A}^{cc} \end{bmatrix} \begin{bmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \\ \vdots \\ \mathbf{x}^c \end{bmatrix} + \begin{bmatrix} \mathbf{Y}^{11} & \mathbf{Y}^{12} & \dots & \mathbf{Y}^{1c} \\ \mathbf{Y}^{21} & \mathbf{Y}^{22} & \dots & \mathbf{Y}^{2c} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{Y}^{c1} & \mathbf{Y}^{c2} & \dots & \mathbf{Y}^{cc} \end{bmatrix} \begin{bmatrix} \mathbf{i} \\ \mathbf{i} \\ \vdots \\ \mathbf{i} \end{bmatrix} \tag{11}$$

The new **x**, **A** and **Y** matrices will have the new dimensions of $(nc) \times 1$, $(nc) \times (nc)$ and $(nc) \times (fc)$, respectively. Considering regions r and s as two regions in the MRIOT, we have the following relationships: $\mathbf{A}^{rr}$ and $\mathbf{A}^{ss}$ are the domestic technical requirement matrices for regions r and s, respectively. It describes inputs to domestic industries sourced from domestic industries. The off-diagonal **A** matrices represent trade of intermediate inputs between regions. From the point of view of region r, matrix $\mathbf{A}^{sr}$ describes inputs to domestic industries sourced from industries in region s, and $\mathbf{A}^{rs}$ describes exports from region r to industries in region s. Similarly, matrices $\mathbf{Y}^{rr}$, $\mathbf{Y}^{sr}$ and $\mathbf{Y}^{rs}$ denote, respectively, final demand of consumers in region r sourced from domestic industries, imported directly to final consumers from industries in region s, and products exported from domestic industries directly to consumers in region s.

MRIOT describe trade flows and consumption in different regions. It can be regions within a country, such as provinces in China[115]; countries within a region, such as countries in the European Union[116]; or global MRIOT, which describe selected countries plus one or more "Rest of the World" regions[117–119]. In this thesis. I use MRIO to refer to global MRIO tables.

MRIO analysis is ideal for studying environmental and social effects linked to final consumption, as it can track both the origin of the impacts (where in the supply chain and in the world it happens) as well as which final products consumed drive the impacts. For that, we extend the MRIOT with social and environmental extensions. An environmentally-extended MRIO (EE-MRIO) table with three regions is illustrated in Figure 4. It comprises of, besides the aforementioned matrices, a matrix with social and environmental extensions **F** which shows all direct social or environmental effects (such as number of workers, kg of CO_2 emissions or kWh of energy used) in each industry and country. It has dimensions $k \times (nc)$, where k is the number of indicators in the extensions.

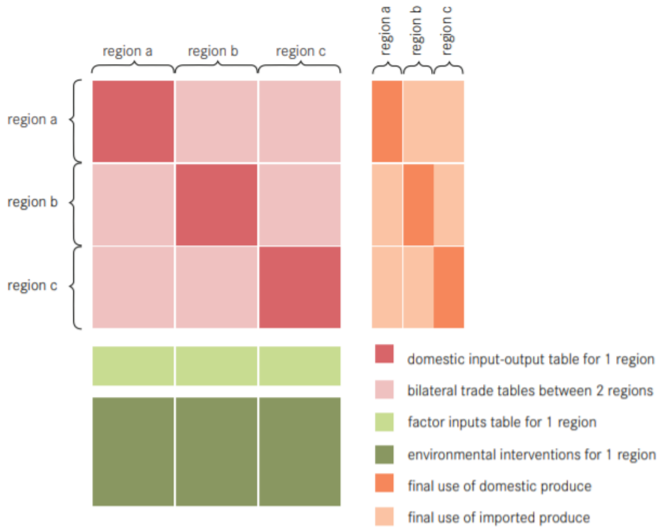

Figure 4. Representation of an environmentally-extended multi-regional input-output table with three regions, from Tukker et al. (2014)[52]. Each block in the legend represent one block in the figure.

Similar to the **A** matrix, we can define a social or environmental coefficients matrix **S**, which describe direct social and environmental effects related to each unit of output in each industry. Using these coefficients, we can calculate footprints (**Q**), where we allocate upstream supply chains effects to final products consumed, similarly to equation 7:

$$\mathbf{S} = \mathbf{F}\hat{\mathbf{x}}^{-1} \tag{12}$$

$$\mathbf{Q} = \mathbf{SLY} \tag{13}$$

Footprints **Q** represent the effects *embodied* in consumption, that is, in the upstream supply chain of final consumption of products. Through eq. 13 we can track the origin of impacts (i.e. *where* impacts occur) and destination of impacts (i.e. *which final consumption* drives the impacts).

2.1.2. Terminology used in this thesis

I clarify below the terminology used throughout the next sessions on the perspective of country r. Here, $\mathbf{x}^r$ and $\mathbf{y}^r$ represent all production and all consumption of country r, $\mathbf{x}^{rs}$ and $\mathbf{y}^{rs}$

represent flows between r and s, and $^{\cdot r}$ and $^{r\cdot}$ represents flows to and from all regions, respectively:

- *Territorial impacts* or *production-based impacts:* are impacts happening in country r and associated to all production from country r, which includes production for domestic consumption and for exports:

$$t^r = \mathbf{S}^r\mathbf{x}^r = \mathbf{S}^r\mathbf{x}^d + \mathbf{S}^r\mathbf{x}^e = \mathbf{S}^r\mathbf{L}^{rr}\mathbf{x}^{rr} + \sum_{s\neq r}\mathbf{S}^r\mathbf{L}^{rr}\mathbf{y}^{rs}$$

- *Consumption-based impacts, impacts footprint,* or *impacts embodied in consumption*: are impacts happening in all countries (including country r) in the supply chain of final consumption of country r:

$$q^r = \mathbf{SLy}^r$$

- *Impacts embodied in domestic consumption* or *domestic impacts*: are impacts happening in country r embodied in products consumed in region r:

$$q^{d,r} = \mathbf{S}^r\mathbf{x}^d = \mathbf{S}^r\mathbf{L}^{rr}\mathbf{x}^{rr}$$

- *Impacts embodied in imports* or *imported impacts*: are impacts happening in all other countries (excluding country r) embodied in products consumed in region r, either purchased from domestic industries or directly imported to final consumers. Imported impacts from country s to r can occur even if country s does not directly trade with country r. For example, if country s exports steel to country b, which in turns exports cars to final consumers in country r:

$$q^{m,r} = \sum_{s\neq r}\mathbf{S}^s\mathbf{L}^{s\cdot}\mathbf{y}^{\cdot r}$$

- *Impacts embodied in exports* or *exported impacts*: are impacts happening in country r embodied in all exports from country r. Like with *imported impacts*, exported impacts from country r to s can occur even if country r does not directly trade with country s:

$$q^{e,r} = \mathbf{S}^r\mathbf{x}^e = \sum_{s\neq r}\mathbf{S}^r\mathbf{L}^{r\cdot}\mathbf{y}^{\cdot s}$$

- *Impacts embodied in net trade*: are the difference of impacts embodied in exports and those embodied in imports:

$$q^{net,r} = q^{e,r} - q^{m,r}$$

2.2. Data

Although IO models with bilateral trade were used since the 1990s to analyse carbon embodied in traded goods[120], major advances in the development of MRIO databases have happened in the past ten years. Towards the end of the 2000s, the analysis of economic and environmental effects of GVCs became more refined with the development of MRIO models based on data from harmonized IO tables[72], introducing a fully coupled model to account for trade of intermediates. After 2010, different MRIO models became publicly available. There are currently five main global MRIO databases. Eora[119,121] has a high country resolution aiming to cover virtually all countries in the world in heterogeneous industry detail. WIOD[117,122,123] provides a time series of annual MRIOTs and is currently the database with more recent constructed time series, covering 43 countries and up to 2014. The OECD-ICIO[124] is the first MRIO published and maintained by a non-academic institution, and includes a time series between 1995 and 2011 for 64 countries. The GTAP-MRIO[125] is a model based on harmonized IO and bilateral trade tables from the Global Trade Analysis Project for 129 countries[126]. Finally, EXIOBASE[118,127,128] was built initially as a one-year table and further expanded to a time series with high industry and product detail and a large number of socioeconomic and environmental extensions.

2.2.1. EXIOBASE

Throughout this thesis, I have relied on data from the three versions of the EE-MRIO database EXIOBASE. This database was developed between 2007 and 2017 throughout three projects financed by the European Union (EU). All versions of EXIOBASE can be downloaded free of charge from www.exiobase.eu. Below, I summarize the development of the database, and the main characteristics of each version are detailed in Table 1.

Table 1. Characteristics of the three EXIOBASE versions. Adapted from Stadler et al. (2018)[118]

	EXIOBASE 1	EXIOBASE 2	EXIOBASE 3
Base year	2000	2007	1995-2011
Products/Industries	129/129	163/200	163/200
Countries [a]	43	43	44
Rest of the World [b]	1	5	5
E: Emissions [c]	26	26	27
E: Water [d]	47	172	194
E: Energy products	69	69	69
E: Non-energy materials	48	48	222
E: Land use	14	15	15
E: Labour	6	6	14

E: Extensions

[a] EU-27 (v1 and v2) and EU-28 (v3) plus 16 major economies: Australia, Brazil, Canada, China, India, Indonesia, Japan, Korea, Mexico, Norway, Russia, South Africa, Switzerland, Taiwan, Turkey, and United States. In the three EXIOBASE versions, the United Kingdom is counted as an EU member.

[b] The five detailed RoW regions are: Rest of Africa, Rest of Asia and the Pacific, Rest of Europe, Rest of Latin America and the Caribbean, and Rest of the Middle East.

[c] Includes emissions from combustion (all versions), non-combustion emissions to air (v2 and v3), and emissions to water and soil from agriculture and waste (v3)

[d] Includes green and blue water, per activity (all versions)

EXIOBASE 1 was developed during the EU's 6th Framework Programme (FP6) project EXIOPOL[h], between 2007 and 2011. EXIOBASE 1 described the global economy for the year 2000 detailed in 129 products and industries and 43 countries plus one aggregated Rest-of-the-World (RoW) region. EXIOBASE 1 also included accounts for 80 resources and 40 emissions. It was among the first global EE-MRIO databases developed for environmental analyses of global value chains. A full description for this database was published by Tukker et al. (2013)[127].

A follow-up project carried out between 2011 and 2014, the EU FP7 project CREEA[i] updated and expanded the database. EXIOBASE 2 is comprised of EE-SUTs for 2007 in higher activity detail (163 industries and 200 products), and further detailed the single RoW region into five continental RoW regions. Major advances for environmental analyses included the

[h] EXIOPOL is an acronym for: "A New Environmental Accounting Framework Using **EX**ternality Data and **I**nput–**O**utput Tools for **POL**icy Analysis"

[i] CREEA is an acronym for: "**C**ompiling and **R**efining **E**nvironmental and **E**conomic **A**ccounts"

development of a physical SUT layer and expansion of the environmental extensions. The construction of EXIOBASE 2 is detailed in Wood et al. (2015)[128].

The two first versions of EXIOBASE provided only snapshots of the economy, and were not necessarily comparable with each other due to differences on data sources, sectorial and spatial aggregation, and methods for building the SUTs. The major advance to study structural changes in the economy came in the EU FP7 project DESIRE[j], which took place between 2014 and 2017. EXIOBASE 3 was expanded to provide a time series of annual EE-MRSUTs for the period of 1995 to 2011, with now-casted tables, in a test version, from 2012 to 2016. EXIOBASE 3 was also extended to include a new EU-member, Croatia, and to provide more detail in environmental and labour accounts. The methods and data to construct EXIOBASE 3 are detailed in Stadler et al. (2018)[118]. The EXIOBASE versions used in each of the articles in this thesis are shown in Table 2.

Table 2. Data used in each of the articles in this thesis. The order of the articles follows the order in the publications list

	EXIOBASE 1	EXIOBASE 2	EXIOBASE 3
Article 1 [a]			■
Article 2 [b]			■
Article 3 [c]	■	■	
Article 4 [d]			■
Article 5 [d]		■	
Article 6 [d]			■
Article 7 [e]		■	

[a] This article reports the production of labour accounts in EXIOBASE 3
[b] The methods described in this article were developed to be consistent with the labour accounts in EXIOBASE 3. This article details the procedures and assumptions of the development of the socioeconomic extensions. The differences between the assumptions for data harmonization and gap-filling in this article and in EXIOBASE 3 labour accounts are pointed out in section 3.1.
[c] For this paper, we used technical coefficients and trade data for 2000 from EXIOBASE 1, rebalanced to match macroeconomic and trade constraints for 2007. Coefficients for net energy use and GHG emissions are from EXIOBASE 1. Labour coefficients, on the other hand, were constructed for EXIOBASE 2, using 2007 data from labour force surveys.
[d] All data used in these papers were from the EXIOBASE version used
[e] Additional labour indicators – vulnerable employment, child labour and hazardous child labour, and forced labour – were built for EXIOBASE 2 during the project PROSUITE.

[j] DESIRE is an acronym for: "**DE**velopment of a **S**ystem of **I**ndicators for a **R**esource **E**fficient Europe"

2.2.2. Development of socioeconomic extensions

The labour extensions in EXIOBASE 2 and 3 were developed in the context of these PhD studies, and are used in publications 3-7 in this thesis and in all other work in the publications list that uses labour data. The methodology and data sources for constructing the dataset for EXIOBASE 2 are reported in the CREEA project deliverable[129]. The development of the labour accounts in EXIOBASE 3 is summarized in section 3.1 and available in articles 1 and 2 (appendix A and B). Between the two EXIOBASE versions, some of the data sources changed to allow for a longer time-series analysis, making direct comparison between databases not recommended.

3. Summaries of articles

This section presents a summary of each of the articles appended to this thesis. Here, I present the main findings of each paper, and how they relate to the set of sub-questions presented in section 1.3. The articles are divided into the development of the dataset and into analytical work.

Development of the socioeconomic dataset

Article 1[130] [Appendix A] describes the data sources and summarized method for building the socioeconomic extensions in EXIOBASE 3.

Article 2[131] [Appendix B] describes the process of creation of the socioeconomic extensions used in this thesis. Although the article reports on building an algorithm to allocate labour data into different MRIO databases, it explains the core data sources and assumptions used for the development of the dataset in EXIOBASE in higher detail than in article 1.

Analysis

Article 3[132] [Appendix C] presents an assessment of labour, energy and greenhouse gas emissions embodied in supply chains in 2007, and analyses how productivity for these three factors change when accounting for imports. It also presents an account of the net trade of labour, energy and greenhouse gas emissions between the EU and the rest of the world.

Article 4[133] [Appendix D] presents a structural decomposition analysis of employment, energy and greenhouse gas emissions between 1995 and 2011, and discusses the contribution of changes in GVCs for these footprints in 44 different countries.

Article 5[134] [Appendix E] quantifies the correlation between production-based and consumption-based environmental indicators for 42 countries and ranks these countries according to environmental pressures embodied in production and consumption. It looks at five different indicators: carbon, water, land, materials, and solid waste and scrap.

Article 6[135] [Appendix F] provides an analysis of employment and wages associated to production and consumption of 30 countries in the European Single Market between 1995 and

2011. It focuses on changes in employment associated with international trade with other countries in the region and with the rest of the world over time.

Article 7[136] [Appendix G] links local labour conditions to final consumption based on a new dataset of social indicators. It presents the social impacts embodied in traded goods between seven aggregated world regions.

3.1. Development of the socioeconomic dataset

EXIOBASE 3 - Supporting Information for labour accounts (Article 1)

Mapping the structure of the global labour market: Developing fully harmonized labour accounts for MRIO analysis (Article 2)

In this section, I summarize articles 1 and 2 together. Article 1 provides data sources and a summarized method specific to EXIOBASE 3. Article 2 provides a more detailed account on the construction of socioeconomic extensions for MRIO models, making explicit all equations and assumptions for data harmonization and gap-filling, which were not present in article 1. Article 2 also presents a critical overview of data available and uncertainties in the data.

The labour extensions in EXIOBASE 3 described in article 1 consist of total employment per gender and three skill levels (high, medium and low), in persons and hours, compensation of employees per gender and skill level, and total vulnerable employment (self-employment), in persons and hours. The follow-up dataset presented in article 2 expands these extensions by providing employees and self-employment per gender, in persons and hours, full-time equivalents in total employment per gender, and improves the data and calculation of the share of wages per gender and skill level. The data are available in harmonized time series for 44 countries plus five RoW regions. In EXIOBASE 3, this time series covers the period from 1995 to 2012, and the dataset described in article 2 provides data up to 2015.

The main objective of this dataset is to provide a base for analyses of changes in the structure of the global labour market over time. It is not meant to be a used as a guide for detailed accounts of the labour force in a specific country, industry and year, as the level of detail in the original data are, in many cases, lower than in the resulting dataset. We thus prioritized data sources that provides the best possible information to build a consistent time series. To maintain simplicity and for ease of update, we prioritized international repositories for economic and labour statistics. Three main databases were used: ILOSTAT[137], Eurostat[138] and OECD Stats[139]. These three statistical databases have pros and cons. ILOSTAT provides long time series and country coverage as well as a high number of labour indicators. However, the highest industry classification is top-level ISIC Rev. 4, with 21 industries. The main drawback is that data from the International Labour Organization (ILO) have no detail for different manufacturing industries. Eurostat also provides a high number of indicators, most of them with long time series. It also provides good industry detail – up to 64 individual industries for data from national accounts (NA) and 87 from labour force surveys (LFS), and the data are mostly harmonized through the available time series. The main disadvantage of this data source is the limited country availability, as it only covers European countries. OECD Stats provide data with long time series and high industry detail (up to 85 industries), mostly already harmonized, but it has limited labour indicators (no gender-specific data) and country availability. When crucial information was missing (for example, work in manufacturing industries in China, or skilled work in China and the United States), these data sources were complemented with some specific additional sources, detailed in articles 1 and 2. For total employment, employees and hours worked, the priority was given to higher industry detail. Unlike previous studies[81,140], data from ILO is set as lowest priority due to high industry aggregation.

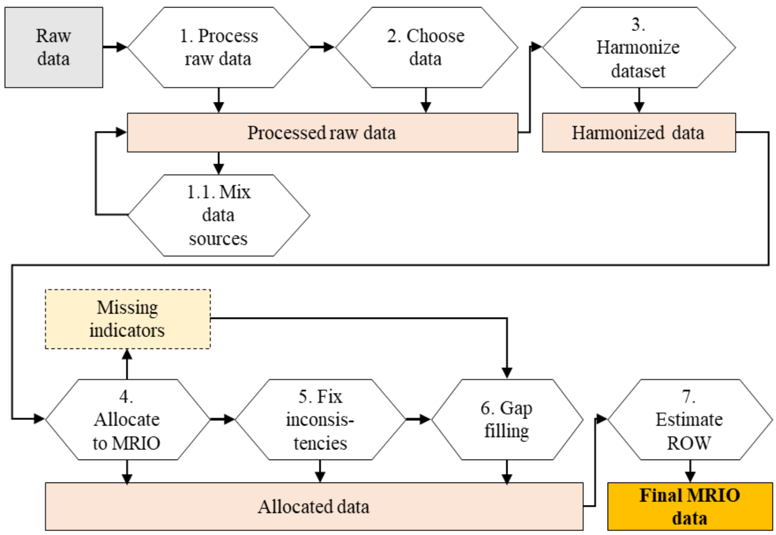

Figure 5. Flowchart of the main steps for building the labour extensions for the MRIO datasets from the source (raw) data. From Simas et al. (2018c)[131]

The process of building the labour extensions for the MRIO databases followed seven steps, illustrated in Figure 5. The harmonization process is the core of the method. It ensures that, over the time series, all indicators are consistent (normalized to total employment), industry classification for all indicators is the best available in the period, and that the time series is not missing any year for the indicators available. This is because the available raw data downloaded from the original sources is often incomplete, changes classifications, and is sometimes conflicting. For a same country and indicator, data quality and classification ranging from 1995 to 2015 was often heterogeneous. Article 1 provides a list of countries with changing industry classification in the period. We harmonize industry classification over the time series to guarantee that we keep differences on labour costs or labour productivities between industries to the best available data, and therefore not use different assumptions when allocating data to the MRIO industries. This harmonization is done by distributing labour from the aggregated industries based on the share of compensation of employees (COE) in the most disaggregated ones. We then estimate missing years on known indicators based on constant growth rates of the relationship between employed persons and COE (for estimating missing total employment) or between other labour indicators and total employment for the closes two years with existing data. In some cases, we combine higher detailed data (for example, work per occupation in high industry detail published by Eurostat) with longer, but more aggregated, time series. In this case, we apply changes over time from a reference dataset (with longer time series) to the preferred dataset (with higher industry detail), and this depends on both datasets having at least one year in common. Article 2 provides a detailed description of steps in the harmonization process and main assumptions and mathematical relationships.

The allocation of the harmonized time series to the MRIO industries is done according to economic data for COE. After allocation to MRIO industries, we check for consistencies between the monetary and labour data, making sure that there is no sector with COE and no labour, or vice-versa. We then readjust the other labour indicators to match the adjusted employment. After we have consistent allocated labour extensions, we estimate missing indicators through a gap-filling function that uses weighted coefficients for industries (full industry resolution in article 1, aggregated in six broad industries in article 2) from other countries in the MRIO. The final step is estimating the RoW regions, based on estimates of total employment from the International Labour Organization, and all other indicators are estimated through the gap-filling function. In EXIOBASE 3 (article 1) we used specific countries as proxies to create the RoW regions. In article 2, however, we use the average of all other countries in EXIOBASE to estimate the relationship between the remaining labour indicators and total employment.

There are limitations and uncertainties in the final extensions built with this process. While we can improve the methods to estimate the gaps in the available data, any estimation carries assumptions and uncertainties. Major improvements have been made on data collection and reporting by statistical offices, not only in developed economies, but also in emerging countries. However, there are substantial data gaps and inconsistencies in the first half of the time series. Data availability and consistency are much better for developed economies, whereas there is a higher level of uncertainty for labour-intensive developing economies whereas higher share of data had to be estimated. Although some of the most common indicators – total employment, employment hours – are mostly available throughout the time series for most countries, this is not the case for data on occupations or skill levels, especially regarding gender, hours worked, and wage differences.

3.2. Analysis

3.2.1. Labour embodied in trade: The role of labour and energy productivity and implications for greenhouse gas emissions (Article 3)

In this article, we quantified labour, energy and GHG emissions embodied in traded goods in 2007 and introduced a consumption-based (CB) metric for productivity. We defined the original production-based (PB) productivity measured as the GDP created by domestic industries divided by production-based requirements: $p_{TB}^{r} = GDP/t^{r}$. In contrast, we defined a new CB productivity metric as the gross national expenditure (total final consumption) divided by national footprints: $p_{CB}^{r} = GNE/q^{r}$. We also quantified the impacts embodied in the net trade of Europe with the other regions in order to identify trade-offs between employment and GHG emissions embodied in traded products.

We show that shifting from PB to CB productivity significantly reduced productivity differences among countries, but there was still a meaningful relationship between the development stage of the country (measured in GDP per capita in purchasing power parity, PPP) and productivity levels for all indicators. This trend is more accentuated for high-income countries (HIC). Labour productivity decreased between 25-50% in HIC countries, with highest declines in Norway, Luxembourg, Denmark, Ireland, and the Netherlands. Most HIC also presented declines in energy (up to 45%) and GHG productivity (up to 55%), with the exception of the United States, Canada and Japan, which improved their productivity, and Belgium, who remained relatively stable. Australia presented a decline in energy productivity, but an improvement regarding GHG, due to its coal-intensive energy mix. Middle and lower income countries in Eastern and South-Eastern Europe presented lower absolute changes on energy and GHG productivities, but higher relative decline than HIC.

The almost linear relationship between territorial labour productivity at the national level and total GDP per capita of a country is expected due to both concepts being nearly overlapping. The amount of people in employment is a function of population. However, the losses of labour productivity when shifting to CB was higher than we had expected. The low productivity in low-income countries (LIC) mean that (1) labour costs are smaller in LIC, as labour compensation is a component of value added; and (2) a large amount of persons at work are embodied in exports from LIC. Therefore, exports from LIC to HIC lead to not only high labour footprints, but also a disparity between the distribution of labour and wages in GVCs. However, we also show that LIC also present lower labour and carbon productivities, and outsourcing from HIC to LIC lead to not only losses of productivity, but also a higher volume of energy and carbon emissions embodied in international trade.

We further investigated the balance of labour, energy and GHG emissions embodied in the net trade of the EU-27 with the rest of the world. We showed that, even though Europe is a net monetary exporter, it is a net importer of all indicators. Labour embodied in net imports were located, mostly, in labour-intensive industries and service sectors in developing countries: China (in agriculture, clothing, electronics and services), India (in agriculture, clothing and service), Indonesia (in agriculture), Russia (in services), and the RoW (in agriculture, electronics and services). Most energy and carbon emissions embodied in net imports originated in energy-intensive production in countries with high share of fossil fuels in its energy mix: Russia, China, India, South Africa, and the RoW. On the other hand, Europe was a net exporter of labour to four HIC (Norway, Switzerland, the United States and Australia); of energy to Mexico, Switzerland and Turkey; and of GHG emissions to the United States, Japan, Mexico, Australia and Switzerland. Although there is a substantial amount of energy, GHG emissions, and especially labour embodied in imports from the RoW, this region comprises approximately 150 countries that together accounted for around 11% of global GDP and 35% of global population. Most countries in the RoW are middle- and low-income countries, with relatively low labour productivity, but productivity in each of these countries likely varies. Thus, factors embodied in RoW's exports present a high uncertainty.

The main contribution of this article was showing that, in a scenario where increasing outsourcing happen to countries with lower labour costs, the relocation of labour-intensive manufacturing stages to lower-income countries can lead to higher overall environmental pressures due to lower energy and carbon productivities of developing economies. This article contributed to **sub-question 1** by providing an assessment of the productivities and distribution of labour, energy and emissions in GVCs.

The main uncertainty from the analysis is in the combination of different EXIOBASE versions. We used the **A** matrix from 2000 rebalanced to meet 2007 macroeconomic constraints for industry GDP growth and bilateral trade, static **s** vectors for GHG emissions and net energy use from 2000, and a compiled **s** vector for labour from 2007. This yields uncertainties to the analysis. First, using a corrected **A** matrix assumes the main production and trade structures to remain relatively static over time. A structural decomposition analysis between EXIOBASE 1 deflated to 2007 prices and the compiled 2007 MRIOT in EXIOBASE 2 has shown to present significant differences between the two datasets, mostly due to important changes in global value chains in the period[141]. Much of the changes in the production structure that happened in the period were not fully captured. The use of static **s** vectors for GHG emissions and energy also assume that the technology used remained static, and volume of production was the only driver for changes of each industry's direct emissions and energy use. This is a weak assumption, and it renders the parallel analysis to 2007 labour data not directly comparable. However, by the time of this publication, EXIOBASE 2 was still under construction. Although the origin for net imports of energy and GHG emissions by Europe changed from these results to the final EXIOBASE 2 (as seen in Figure 3), the main trends for net imports of resources and for productivity observed in the study are maintained when using the new EXIOBASE versions.

3.2.2. Drivers of employment and carbon emissions in global value chains (Article 4)

In this article, we quantified the contribution of different drivers in the development of labour, energy and carbon footprints. This analysis was performed for the period between 1995 and 2011 for 44 different countries. We performed a structural decomposition analysis (SDA), separating the drivers for footprint growth into five different determinants: domestic factor intensity, foreign factor intensity, production structure, trade structure, and consumption. Factor intensity (the **s** vector.) combines gains in productivity and the length of supply chains. The production structures comprises the domestic industry requirements, and it accounts for all inputs needed for domestic production, regardless of their origin. This production structure also reflects the production specialization in global value chains, although we cannot separate this effect due to technological changes in efficiency or to fragmentation of production. Changes in trade structure comprise outsourcing and changes in trade patterns, both for intermediate products and for final products. Changes in consumption include composition of products consumed, the volume of consumption per capita, population growth, and household direct energy consumption and GHG emissions.

We show that the same drivers for increased GHG footprints have also led to a higher number of people in employment, and that the contribution of changes in GVCs varies between countries. Labour, energy and GHG footprints of developing economies were mainly driven by domestic factors, especially productivity improvements in national industries and increased consumption. These results confirm previous SDA studies[50,89,142]. However, changes in outsourcing and international sourcing had important effects for the increase of labour, energy and carbon footprints in high-income countries in Europe and Asia. In these regions, foreign productivity improvements were as important as domestic productivity gains. In North America, changes in trade structure and gains in foreign labour intensity were important drivers for labour footprints, while production structures were more important for energy and GHG emissions. However, increased consumption was a far more important driver for footprint growth for all indicators.

We further identified the differences among countries within the four regions studied. There are two main groups within Europe, which have similar patterns of drivers of growth of labour, energy and carbon footprints. First, the older European Union members (EU-15), together with Norway and Switzerland, present a pattern of high contribution of trade to increased labour, energy and GHG footprints. The second group comprises the new EU members, and is characterized by important structural changes in the economy in the past decades after the dissolution of the Soviet Union. Among these new EU members there are some of the fastest growing economies in Europe, with consumption patterns and lifestyles quickly catching up to the countries in the first group. Within this group, there are countries for which changes in the production structure has led to more labour-intensive and less energy-intensive production. The patterns for North America are dominated by the United States', while for the developing economies, it is China who dominates the analysis for energy and GHG emissions. In North America, Mexico presented very different patterns: domestic technology improvements did not offset the effects of increased consumption for energy and GHG footprints, and foreign technology improvements were the main driver for reduced acceleration of footprint growth. Among the developing economies, footprints were mainly driven by changes in domestic factor intensity, consumption per capita, and population growth. Changes in the production structure led to higher GHG footprints, pointing to higher industrialization of these developing economies. For labour footprints, the type of products consumed led to significant reductions in labour footprints in all periods, while energy consumption by households was an important driver for increased energy footprints. Changes in consumption patterns and higher energy use by households might reflect higher urbanization, increased social and economic development leading to higher access to goods and services and to modern energy sources, and to the convergence of lifestyles in the world.

The main contribution of this article was to show that changes in GVCs have been important drivers for both labour and carbon footprints of developed economies, and there are trade-offs to consider for decarbonization of GVCs. In order to decrease carbon footprints of high-income economies (outsourcers), it is as important to decarbonize production processes in the upstream supply chain as it is to improve carbon efficiency of domestic industries. This article contributed to **sub-question 1** by providing an assessment of the temporal dimension of the distribution of labour, energy and emissions in GVCs.

3.2.3. Correlation between production and consumption-based environmental indicators: The link to affluence and the effect on ranking environmental performance of countries (Article 5)

In this article, we quantified how different environmental indicators are correlated at the national level, and further compared how countries rank regarding PB and CB environmental pressures. The main goal was to look at how complementary are environmental indicators dashboards to assess environmental performance of countries. We looked at five indicators that have been frequently used for such assessments: GHG emissions, materials, water consumption, land use and waste. We also compared the environmental footprints with the ecological footprint[143] and with GPD adjusted for PPP. All indicators were compared on per capita basis. With the exception of the ecological footprint, all environmental indicators were calculated using EXIOBASE 2. The 42 countries[k] studied in the article represented the majority of environmental pressures worldwide in 2007. For PB pressures, these countries were responsible for around 80% of global GHG emissions, 75% of domestic extraction used, over 65% of blue water consumption, and around 60% of global land use. For CB footprints, these countries present an even higher contribution to global environmental pressures: over 85% for GHG emissions and materials, and around 80% for water and land footprints.

We find that environmental pressures caused by domestic production processes are mostly not or only weakly correlated with GDP. The lack of strong correlations on PB indicators likely occurs due to a range of specific national characteristics, such as differences in natural resource availability, economic specialization, subsidies and national industrial policies, or due to

[k] In this article, we excluded Taiwan from the analysis due to the lack of ecological footprint indicator for this country.

countries having taken different decisions about avoiding or mitigating such pressures. Therefore, to assess environmental performance of countries from a PB perspective, different environmental accounts should be considered simultaneously, as they complement each other. CB accounts, meanwhile, show much stronger correlation to each other and to GDP. We find that considering the effect of trade either introduces or significantly strengthens the correlations among the different pressure indicators, as we subtract things that are unique for countries and add from a common pool. The increasing specialization of countries in different products and production stages contributes to differences in PB resource use and environmental pressures, while increasingly similar lifestyles regarding types of goods and services consumed contribute to the high correlation of footprint indicators.

When ranking countries based on their environmental indicators per capita, we see an inconsistent pattern regarding PB pressures, but a very similar one when internalizing GVC effects, where more affluent countries rank higher on most of the environmental pressures. Some outliers exist, such as Sweden who ranks much lower on water and carbon footprints than in other indicators, Portugal and Malta who rank much higher on water footprints, and Russia who rank high on land and waste, but low on other indicators. These cases show that, while there is much more consistency in the environmental performance of countries when looking through a CB approach, there might be important differences in the resource appropriation of different countries. A more detailed study on why these differences exist and how they have changed over the years is still needed to understand how much of these outliers are due to resource use by national industries or through economic specialization in GVCs, and might contribute to understanding how to improve decoupling of environmental footprints from GDP per capita.

The high correlation of CB environmental pressures indicate that the different environmental footprints are strongly coupled to some underlying mechanisms in the countries' socioeconomic metabolism. Decoupling one indicator from affluence or wellbeing may depend on the simultaneous decoupling of others, which means that sustainable development may represent a much larger challenge than improving technological factors in economic production within national boundaries. This article contributed to **sub-questions 1 and 3**. To the former, due to understanding the contribution of GVCs on environmental pressures (besides GHG emissions) associated to consumption, and that trade results in reduction of differences among countries, making the final pressures of countries more homogeneous. The contribution to the latter was on the linking of economic development stages, measured in GDP per capita, with global environmental pressures. As GDP per capita is, at least partially, correlated to other well-being measures, achieving higher economic development in LIC would mean also generating global environmental pressures that could exceed safe planetary boundaries.

3.2.4. Jobs in global value chains: Employment and wages in European production and consumption (Article 6)

In this article, we quantified labour market effects of European production and consumption between 1995 and 2011, focusing on two perspectives. First, we looked at changes in origin and composition of European labour demand (for European consumption) over time. Second, we looked at how reduced consumption – and, especially, reduced imports – during the financial crisis affected domestic, regional and global labour markets. We looked at three labour market indicators: wages adjusted to PPP, in constant 2010 international $, total employment per skill level, and vulnerable employment. Vulnerable workers are defined as those with no formal work arrangements and more likely to lack decent work condition and to lose employment during economic recessions. It includes employers, own-account workers and paid or unpaid family workers with no formal employment contracts. The share of employers on self-employment compared to own-accountant workers and family workers is small, estimated to be lower than 10% worldwide, and even lower in low-income regions[144]. The vulnerability aspect of self-employment does not necessarily correlate with low income and low financial resilience. However, in developing countries, a majority of workers in self-employment are in poor households[145]. The jobs and wages in global value chains (GVC jobs and GVC wages) are separated between trade with other European countries (intra-European trade) and with the rest of the world (RoW). Intra-European trade here represents only trade for final products consumed in Europe. Trade of intermediate products that are further processed in Europe and end embodied in final consumption of non-European countries is considered exports to the RoW (following terminology explained in section 2.1.2).

We show that almost half of all employment embodied in European consumption happens elsewhere, mainly in Africa and Asia, and 45% of this employment in other continents is comprised of workers in vulnerable condition. We also show that over three-quarters of all wages embodied in European consumption were paid to European workers, and over three-quarters of all high-skilled workers were in Europe, concluding that the region has increased sourcing from low-cost labour from other countries, while retaining high-income work. We highlighted the dependence on foreign labour of European consumption and showed that, with decreased consumption during the financial crisis, reduced imports affected mostly workers outside Europe, especially those in self-employment and in low-skilled employment. Before the financial crisis, European countries increased international sourcing rapidly, resulting in a large growth in the volume of jobs and wages embodied in European imports from non-European countries. Annual growth rates for the period between 1995 and 2007 averaged around 6% and 4% of for wages and labour embodied in European imports from the RoW. However, in the period between 2007 and 2009, both wages and employment decreased on average 4% per year, but wages and labour embodied in European exports to the RoW remained somewhat constant, demonstrating a resilience of European exports to the crisis. Further analysis can show whether this resilience come from the amount of services exported, which were less affected than trade in durable goods[146], or due to a shift in exports destination to regions which were less affected by the recession[30].

Most European countries have increased the participation in jobs and wages in GVCs. This applies to both imports and exports. Overall, European imports generated more jobs outside Europe than jobs in Europe for exports, and most European countries increased the volume of wages and jobs associated with imports in higher intensity than with exports. This is understandable as Europe absorbs around 30% of global gross imports, at the same time that it corresponds to around 10% of the global population. The volume of wages and jobs embodied in imports and exports increased for nearly all countries, both traded within Europe and with non-European countries. Surprisingly, although the countries have become more integrated in the European Single Market (ESM), jobs and wages in imports and exports to non-European countries grew with higher intensity than that to other ESM countries. There are exception, such as some of the new EU members from Eastern Europe. For all but one country, the creation of jobs in the rest of the world represented an addition, not a substitution, to jobs created in other European countries. The financial crisis in 2008 led to negative effects in the labour markets both within and outside Europe. Although the effects of reduced European consumption affected workers in the rest of the world in higher intensity, the intra-European trade also suffered the effects of the crisis. As countries turned to domestic industries to minimize the effects of the recession on the labour market, most European countries saw significant reductions in jobs and wages in products traded with other European countries.

This article contributed to **sub-questions 1** and **2**. To sub-question 1 due to the quantification of labour and wages in global value chains associated to European production and consumption, and how this has changed over time and for different countries. To sub-question 2 by analysing and discussing vulnerable employment embodied in exports from developing to developed countries.

3.2.5. The "Bad Labour" Footprint: Quantifying the social impacts of globalization (Article 7)

In this article, we linked local labour conditions to global consumption, with focus on internationally traded goods. We used the expression 'bad labour' to refer to six indicators of undesirable labour conditions: occupational health damage, vulnerable employment, gender inequality, prevalence of unskilled and low-skilled labour, child labour, and forced labour. We used the (then) newly developed EXIOBASE 2 to model the bad labour footprints, making use of its newly disaggregation of the RoW in five continental regions. Due to the fact that (1) data for occupational health damage and for child and forced labour had low spatial and industry detail and (2) a high amount of work in general and *bad labour* in particular were allocated to the EXIOBASE RoW regions, we aggregated the results to seven continental regions and eight consumption categories. This was done in order to avoid a false representation of the resolution we could obtain from the data we used.

We highlight the contribution of inter-regional imports to the footprints of high-income regions. For North America and Europe OECD, respectively, imports from other regions accounted for about 40% and 50% of total employment footprints in 2007, and those shares are even higher for low-skilled labour, of about 70% and 80%. At the same time, imports to these regions represented approximately 60-75% of all workers in bad labour conditions in their supply chains. On the other hand, over 95% of the workers in undesirable conditions embodied in consumption of Asia and the Pacific and of Africa are employed inside the region.

Furthermore, the intensity of these bad labour indicators were not homogeneous comparing imports, exports and domestic production. The intensities were calculated as rates of undesirable labour over all labour embodied in each of these measures, for example in share of workers in vulnerable condition out of total workers, or persons in child labour per 1000 total persons in labour. As expected, imports to North America and Europe OECD were more intense in undesirable labour conditions than its production for domestic consumption and for exports. Imports to these regions had intensities 1.7-3.6 higher than domestic production, while exports were 0.7-1.2 as high as domestic production. North American exports were more intense in child labour than its domestic production, while all European exports had a lower intensity on exported products. Exports from Latin America were around 2.5 more intense in child and forced labour than domestic production, the highest difference in any indicator in any region. This reflects the high specialization of inter-regional exports from Latin American countries of products made with poor labour conditions, mostly from extractive industries.

Most undesirable work conditions happen in the supply chain of food products. Although corresponding to one third of global employment in 2007, the consumption of food products embodied around 40% of all occupational health damage, 55% of vulnerable workers, and over 60% of child and forced labour. It also had the highest incidence of low-skilled workers – over 55% of all workers in unskilled or low-skilled work. The expenditure on construction employed around 6% of all workers worldwide, but it concentrated almost 20% of all occupational health damage, and had the lowest female participation: only around 15% of all workers in supply chain of the construction industry worldwide were women. Although the supply chain of clothes are widely associated with undesirable labour conditions, as seen in the collapse of the Rana Plaza building in 2013 killing over one thousand people and in the numerous reports of sweatshops associated with exports, the consumption of clothes and wearing apparel products only correspond to less than 2% of all undesirable labour conditions. That is because total employment in the upstream supply chain of these products account for less than 2% of total workers worldwide.

Most bad labour happen in developing countries, reflecting higher poverty rates and to high population allied to low labour productivity. Furthermore, around 80-85% of all undesirable labour conditions happen in the production of goods and services consumed domestically or traded within the same region, and are not associated to global (inter-regional) value chains. However, intra-regional trade might have an important contribution to total GVC-related flows. An analysis of the results with the full MRIO for the original indicators from EXIOBASE revealed 22% of total labour, 25% of vulnerable employment and 19% of low-skilled labour were embodied in internationally traded goods between the 43 countries and with the five RoW regions, against 16%, 19% and 15% in the aggregated inter-regional model.

The main contribution of this article was the development of a new set of social indicators and an analysis of these indicators within a same framework, revealing the similarities and differences between them. This article contributed to answering **sub-question 2**, providing a quantification of social impacts associated with the labour distribution in GVCs. However, there are some limitations in the analysis, mostly regarding data. Data for child and forced labour are highly uncertain due to statistics collection and availability. Due to the illegal and hidden nature of these workers these data are often not collected or reported, thus we rely on rough estimates by international agencies for broader regions and economic activities.

4. Discussion

Throughout the years I worked on the articles on this thesis, the MRIO field developed rapidly and intensively. After the publication of the different MRIO databases from early 2010s, there have been a growing number of studies on environmental indicators embodied in internationally traded products. The socioeconomic dataset I developed for EXIOBASE 2 and 3 – for which core methods and data sources are described in Articles 1 and 2 – constitute the backbone of this thesis. The complexity and the indicators coverage in EXIOBASE 3 increased compared to the previous version. This new set of indicators allowed the use of EXIOBASE for analysis of labour and social impacts embodied in GVCs, complementing the environmental analysis for which this database was created. However, this thesis is not a description of the dataset. The analysis contained in the five articles (A3 to A7) summarized in section 3.2 and available in appendices C-G contribute to the assessment of the distribution (and redistribution) of labour in GVCs and the social impacts and environmental pressures from it.

As discussed in section 1, the global economy has become more fragmented, and moved from regional production networks to increasing sourcing from regions further away. This is especially the case with developed regions in North America and Europe. Increased sourcing from, especially, Asia (and China in particular) until 2007 led to a redistribution of labour markets, as shown in the articles in this thesis (A3, A4, A6, A7). This change occurred mainly for people in employment, leading to increased labour embodied in imports especially from labour-intensive economies, although maintaining most of wages and high-skilled positions in the regions. I showed briefly this pattern of labour versus wages in net trade of Europe in A3, and presented a detailed analysis in A6. Over the past four years, other studies comparing labour and wages associated to GVCs have shown the same pattern[81,82,84,85]. This pattern of distribution of labour and wages correlates well with the 'smile curve' in figure 2.

One aspect that this redistribution of work in GVCs raises is: with an increasing share of workers associated with foreign trade, what are the social implications for workers, especially in low-income countries? Analysing the changes in labour conditions of workers in the supply chain of traded products (A6 and A7) can provide important information to guarantee decent work and social sustainability in global value chains. While any social impact of GVCs, negative or positive, is the responsibility of the consumer, both consumers and producers benefit from trade. The consumer, due to lower production costs (and, thus, higher purchasing power) and the availability of a higher variety of goods and services. The producer, through the creation of jobs, income and GDP, besides any other positive spillovers in the economy such as innovation and gains in productivity[147,148]. However, international trade is not always necessarily a win-win situation[149–151]. Achieving the Sustainable Development Goals (SDGs) for growth and decent work, including resilience of low-income workers in periods of economic stagnation or recession (A6), requires cooperation between producers, consumers and, also, large companies and retailers that drive the demand for goods and services in local and regional supply chains[152].

Achieving SDGs in an interconnected supply chain pose further challenges and trade-offs. While international trade generates has contributed to create employment and wages – and developing countries have benefitted economically from exports to the developed world – it has also contributed to the displacement of resource-intensive and pollution-intensive production stages from advanced to developing economies. The early discussions regarding carbon leakage focused on whether the adoption of climate policies in developed economies would lead to increased outsourcing to countries without climate policies. However, the 'natural' outsourcing of production stages due to costs, resource endowments, and other factors such as policies and subsidies, cannot be dismissed in the 'outsourcing' of environmental pressures. This thesis points to the issue of the overall disparate productivity differences between the 'outsourcer' and 'outsourcee' (A3) and the impacts for the displacement and growth of environmental pressures. While the usual 'outsourcees' have improved their technology to become more energy and carbon efficient (A4), improved sophistication of exports[153,154], the migration of 'sunset industries'[1] to emerging countries[34,155] , and raising labour productivity and labour costs can lead to these regions increasingly become 'outsourcers' to less-developed economies with even lower energy and carbon productivities. It is clear, then, that mitigating climate change (and social and environmental impacts and pressures in general) requires multilateral cooperation between different actors in GVCs.

[1] 'Sunset industries' are industries which are in decline. When losing comparative advantages in the original country [155], they migrate to emerging markets and become 'sunrise industries' – new and innovative industrial activities that can cause positive innovation spillovers.

4.1. Limitations

4.1.1. Limitations of multi-regional input-output analysis

MRIO analysis is a widely used method for GVC analysis, as it offers a complete overview of the entire global production stages. However, this method has two main drawbacks. First, it builds on large data requirements. The development and update of MRIO databases require a large labour input (in several high-skilled persons-year), which renders it quickly lagging behind in terms of data vintage. The latest year available in EXIOBASE (excluding the nowcasted data in test version) is 2011 – seven years ago. Although it has been indicated that international trade has slowed down after the 2008/09 financial crisis[156], it is likely the case that the global economy has changed between 2011 and 2018. Eora has been updated until 2013, and WIOD launched a new version which covers the time period until 2014. However, with the exception of the OECD-ICIO, these MRIO databases require constant funding in order to develop, maintain and update the annual MRIOTs and extensions.

The second drawback is the low industry and country resolution of MRIO databases. While bilateral databases report thousands of goods and services, MRIO developers rely on SUTs available from national statistical offices, often in the resolution of dozens of goods and services. However, for macroeconomic analysis such as the ones in this thesis, the high sector resolution yields low uncertainties[157–159]. Likewise, the high country resolution in EXIOBASE and WIOD do not present substantial problem for the assessment of value added, energy or GHG emissions, as it covers most of the production and consumption of these indicators. However, the aggregated rest of the world regions account for over one third of global land use and labour, and the aggregation of regions with different production structures, income levels and productivities into one single region makes the flows between the explicit countries and the rest of the world regions highly uncertain.

There are also differences evident in comparisons of different MRIO databases. So far, comparative studies have shown up to 10% of difference in carbon footprints calculated with Eora, WIOD, EXIOBASE and GTAP-MRIO[160], and while most of the differences arise from the extensions used, the underlying economic data is also source of difference between different MRIO databases[161]. Steen-Olsen and colleagues[80] list some differences between the economic data treatment in each of the different MRIO databases, and quantify differences in the trade in value added indicator, showing that while domestic value added is somewhat robust, there can be significant differences in value added embodied in exports and imports between the MRIO databases Eora, WIOD and GTAP-MRIO. Therefore, I cannot exclude uncertainties due to the choice of EXIOBASE for the MRIO modelling.

Between the articles in this thesis, there can be differences due to the use of various EXIOBASE versions, as shown in Table 1 (section 2.2). Even though they are close enough, results compiled with different EXIOBASE versions are not directly comparable. For example, GHG footprints calculated for 2007 using EXIOBASE 3 compared to version 2 present a total difference of -5%. Country-specific differences range from -33% to +19%, with higher differences mostly concentrated on countries that have low footprints. There are two main distinctions between the versions: the monetary data and the extensions. The first one rises from differences in the compilation of the SUTs, such as the addition of an extra country in EXIOBASE 3 and the use of different assumptions and approaches in the construction of initial estimates and balanced SUTs and bilateral trade data. The second is due to changes in the construction of the extensions, such as the use of revised data for energy and emissions from the International Energy Agency (IEA); difference in indicators coverage (as shown in Table 1); and use of different data sources and base-years for extrapolation of missing data in the case of other environmental extensions. A comparison of the results for selected indicators of the different EXIOBASE versions is available at www.environmentalfootprints.org.

4.1.2. Data

Throughout the articles, we see a large contribution from developing economies to produce goods consumed in developed economies. While results from different MRIO analyses point to the same pattern (e.g. Alsamawi et al. 2014[81], Mair et al. 2016[85] and Sakai et al. 2017[162]), one issue that we should have in mind is the differences in labour share and productivity in the work allocated to GVCs. The use of average products in GVCs assumes the same share of capital and labour in the production of all goods and services from each activity. However, these can change between regions within a country and between production units – for example farms or factories – aiming to domestic consumption versus exports. One example is presented in article 7, where small and medium family-owned agricultural properties in Brazil in 2006 accounted for 85% of all farms and about 75% of all employment in agriculture, but only 38% of total agricultural GDP, about 25% of agricultural land, and only about 20% of total agricultural exports[163]. Thus, domestic- and exported-oriented production might present very different requirements for production. Although a higher detail of agricultural products in

EXIOBASE might correct some of these disparities, the labour data used to construct the datasets only distinguishes one agricultural sector. A second issue is the inability of separating labour that is embodied in formal and in the informal and non-observed economy We can consider two examples: first, a member of a rural property who produces agricultural goods for their own subsistence; and second, a person who stays at home caring for the house and family, performing unpaid work. Both persons are reported as employed persons in labour force surveys[164], and both account for significant number of persons at work in some countries, especially in developing economies[165]. In the first case, the production of agricultural goods for subsistence can be reported in national accounts[m] but the produced goods do not enter the global value chains, and the employment for subsistence can be allocated towards market flows. In the second case, service activities performed by households for their own use – for example, domestic work and caregiving – are explicitly excluded from the production system in the national accounts[166], and labour reported for these industries are wrongly allocated to producing industries in the economy. However, we still lack information to remove persons employed in the non-observed economy from the labour accounts in MRIO, especially when dealing with large volumes of data for several years and countries.

The non-observed economy represents the share of economic production that is either informal, for own consumption (subsistence), or underground or illegal. While it is hard to distinguish both labour and economic output from the underground and illegal economy, there is a need for improving the comparison between labour and the economic production in the System of National Accounts for subsistence and informal production, as well for informal employment. According to the International Labour Organization, the informal economy accounts for more than half of the global labour force[168]. Informal sectors of the economy and informal work can be related or not to production that can be associated with global value chains. For example,

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[m] In article 2, I affirm: "Generally, neither economic nor physical production/consumption of subsistence farming is included in the input-output system". However, this information is not correct, and here I make a *corrigendum*. The input-output system reflects the data in the System of National Accounts. Whether subsistence production is reported in national statistics depends on whether production for subsistence in a specific industry is "*believed to be quantitatively important in relation to the total supply of that good in a country*"[166]. In that case, subsistence goods are valuated in basic prices at the prices they would be sold in the market. It is rarely the case, however, that these goods are reported separately. For example, the Malawi statistical office differentiates households' production of agricultural goods for own consumption and that sold to the market[167].

informal workers in outsourced companies supplying services to the clothing industry are associated to global value chains – and is how forced labour and child labour can be allocated to traded goods. However, domestic workers and subsistence agriculture cannot. Thus, employment in the agricultural sector are likely to be overestimated in all labour analysis in GVC, as the requirement of agricultural goods by national and international markets do not demand that rural population work in their own farms for subsistence. It is then necessary for MRIO developers to estimate the share of workers who should not be accounted in the MRIO labour extensions in order to improve the reliability of labour analysis in GVCs.

Another aspect is the choice of indicator. All labour quantification in this thesis is done for total persons. This measure might overestimate the disparities between countries regarding labour productivity and labour embodied in production and consumption. This is because we account part-time and full-time workers as equal. Countries differ greatly regarding the amount of workers in part-time jobs, even in developed economies. In the Netherlands, over 35% of all workers work in part-time employment, while this share decreased to around 15% in France, and less than 5% in Russia[169]. Different questions demand the use of different indicators. While I have used the words *jobs* and (*persons in*) *employment* as synonyms throughout the thesis, these concepts are not the same. Labour indicators can be quantified in number of persons in employment, in number of jobs, or in full-time equivalents, and these indicators have different meaning. The number of persons in employment account for all people involved in the workforce. Usually, the industry in which the person is allocated in labour force surveys is the one where the person has its primary job[164]. For a social footprint analysis, this indicator is the most suited, since it provides an account of number of people affected by production and consumption. People can hold multiple jobs, and thus the number of jobs in a country could be higher than the number of persons in employment. In the United States, over 5% of people in employment are estimated to work in more than one job[170]. For a policy-making perspective, the number of jobs can be the most relevant indicator, as it shows the actually job openings or losses due to production fragmentation or due to economic recessions. The final indicator, number of full-time equivalents, normalizes all persons to the number of hours a full-time worker is occupied in work-related activities. It corrects the differences in part-time and full-time work, as well as overtime work, in one single comparable indicator. Full-time equivalents better reflect the amount of hours worked – which is the preferred indicator for use and comparison of country specific and cross-country labour productivity – while providing an indicator that is easier to understand and interpret when studying both effects on labour. This indicator should be used when labour accounts need to be corrected for hours worked, for example, when quantifying the effects of a gender pay gap[171]. Therefore, MRIO databases should ideally comprise these three measures of labour accounts in their extensions.

5. Conclusions and outlook

5.1. Summary and conclusions

The main research question of this thesis was "What have been the social and environmental consequences of the changes in global value chains and how have they shifted in the past decades?". Due to the broad aspect of this question, I then focus on the contribution of this thesis to the three sub-questions presented in section 3.1, namely: the quantification of labour, energy and greenhouse gases in global value chains, the social impacts of this redistribution of labour, and the trade-offs between socioeconomic impacts and environmental pressures in the global economy. This section summarizes main findings and their contribution to these questions.

First, I confirm and quantify the relocation of labour in global value chains, linking production stages to consumption of final goods and services. The relocation of labour-intensive manufacturing stages had a substantial effect on the redistribution and intensity of labour, energy and environmental pressures embodied in consumption and in traded products. This is due to not only the types of goods and services traded, but also how efficiently these goods and services are being produced. While lower energy efficiency and high carbon content of energy systems have increased the volume of greenhouse gases embodied in trade and in the consumption of high-income countries, the lower labour productivity resulted in higher amount of people employed, many of them in developing economies.

This redistribution of labour has positive and negative socioeconomic impacts. First, the generation of employment and, consequently, of income, contributes to provide positive impacts in developing economies. Whilst we do not quantify the effect of job losses due to this outsourcing, our analysis has shown that within Europe, with few exceptions, the foreign increased labour has come in addition, and not in substitution, to domestic employment. The increased exports of developing economies also affected the overall composition of labour in global value chains. On average, developed regions tend to concentrate more high-skilled and high-income workers, with lower degree of vulnerability and less workers in undesirable labour conditions, such as in forced labour and child labour. Workers in low-skilled occupations and in vulnerable employment are more likely to suffer the effects of economic shocks. Therefore, identifying hotspots of positive and negative impacts in global value chains is essential to work multilaterally towards improving labour standards and decent work, as boycotting suppliers with undesirable labour conditions might create even higher social impacts to poor households[172,173].

Finally, it is important to note the trade-off between socioeconomic benefits and environmental pressures in globalized production chains. Changes in technology deployment and policies generate impacts that go beyond their national borders. On one hand, increased industrialization and participation in exports generate employment and income in developing countries, generating positive spillovers in the economy. These economic gains can be important enablers to achieve social development goals. However, as many developing economies present a lower efficiency in the use of resources such as energy and materials, and are further away from the technology frontier than the outsourcers[174], environmental pressures ultimately increase. It is important, then, to identify potentials for productivity improvements and technology diffusion[92,93] in order to reduce environmental pressures in global value chains without impacting workers and income in developing economies.

5.2. Outlook and future work

The challenge of reducing environmental impacts below planetary boundaries while improving the livelihood of the human population is complex. Any policy must take into account the interconnected nature of the global economy and the many trade-offs between the social benefits and negative impacts of the current production system. It is paramount that the negative economic impacts of technology changes and economic restructuring do not fall onto the most vulnerable workers in GVCs. In order to achieve this, we must understand how labour and environmental impacts are interconnected in GVCs.

However, further analysis is required to study the trade-offs in different countries and sectors over time, including comparative analyses between jobs and income losses and gains, in order to improve projections of the potential socioeconomic and environmental effects of policies into the future. For that, it is also vital to improve data reliability for multi-regional input-output databases and for the extended environmental and labour accounts. Furthermore, it is paramount to include a range of methodologies – beyond footprint analyses –in global value chains studies. Assessing the contribution of different actors and their power to provide changes to the economic system will be essential to the study of the benefits and pervasive effects of changes in the global economy.

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7. Appendix

List of appended articles:

A. Simas, M., K. Stadler and R. Wood. 2018b. EXIOBASE 3 - Supporting Information for labor accounts (S7). Supporting information for: Stadler, K. et al. 2018. EXIOBASE 3: Developing a time series of detailed Environmentally Extended Multi-Regional Input-Output tables. Journal of Industrial Ecology 22(3): 502-515.

B. Simas, M., K. Wiebe and R. Wood. 2018c. Mapping the structure of the global labour market: Developing fully harmonized labour accounts for MRIO analysis. *Unsubmitted manuscript.*

C. Simas, M., R. Wood, and E. Hertwich. 2015. Labor Embodied in Trade: The Role of Labor and Energy Productivity and Implications for Greenhouse Gas Emissions. Journal of Industrial Ecology 19(3): 343–356.

D. Simas, M., E. Hertwich and R. Wood. 2018a. Drivers of employment and carbon emissions in global value chains. *Unsubmitted manuscript.*

E. Simas, M., S. Pauliuk, R. Wood, E.G. Hertwich, and K. Stadler. 2017. Correlation between production and consumption-based environmental indicators: The link to affluence and the effect on ranking environmental performance of countries. Ecological Indicators 76: 317–323.

F. Simas, M., K. Wiebe and R. Wood 2018d. Jobs in global value chains: Employment and wages in European production and consumption. *Unsubmitted manuscript.*

G. Simas, M., L. Golsteijn, M. Huijbregts, R. Wood, and E. Hertwich. 2014. The "Bad Labor" Footprint: Quantifying the Social Impacts of Globalization. Sustainability 6(11): 7514–7540.

Appendix A

Simas, M., K. Stadler and R. Wood. 2018b. EXIOBASE 3 - Supporting Information for labor accounts (S7). Supporting information for: Stadler, K. *et al.* 2018. EXIOBASE 3: Developing a time series of detailed Environmentally Extended Multi-Regional Input-Output tables. Journal of Industrial Ecology 22(3): 502-515.

SUPPORTING INFORMATION FOR:

Stadler, K., R. Wood, T. Bulavskaya, C.J. Södersten, M. Simas, S. Schmidt, A. Usubiaga, J. Acosta-Fernández, J. Kuenen, M. Bruckner, S. Giljum, S. Lutter, S. Merciai, J.H. Schmidt, M.C. Theurl, C. Plutzar, T. Kastner, N. Eisenmenger, K.H. Erb, A. de Koning and A. Tukker. 2018. EXIOBASE 3: Developing a time series of detailed Environmentally Extended Multi-Regional Input-Output tables. *Journal of Industrial Ecology.*

Summary

This supporting information describes the collection, processing, and presentation of the socioeconomic extension for EXIOBASE 3. Socioeconomic data in EXIOBASE 3 consist of labor indicators collected for 44 countries plus five 'rest of the world' regions for the period between 1995 and 2012.

EXIOBASE 3

SI_labor
Supporting Information for labor accounts

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1 Compilation of labor accounts

This supplement describes the collection, processing, and presentation of the socioeconomic extension for EXIOBASE 3.

Socioeconomic data in EXIOBASE 3 consist of labor indicators collected for 44 countries plus five 'rest of the world' regions for the period between 1995 and 2012. The indicators available are: compensation of employees distributed by skill level, total employment and hours worked distributed by gender and skill level, and vulnerable employment and hours worked by persons in vulnerable employment.

These indicators represent an expansion of the labor indicators in EXIOBASE 2. The labor data were extended from availability by skill levels to the availability by both skill levels and gender. Vulnerable employment is also a new addition to the socioeconomic indicators in EXIOBASE 3.

In the following sections we describe the indicators used, their characteristics, and data sources. It follows a discussion about the adjustments of the time series, uncertainties, and key assumptions used to fill in the existing gaps in available statistics.

2 Method

2.1 Indicators and data sources

Labor-related data were collected for each country and economic sector. These data reflect the labor quantity as well as the labor quality.

For labor quantity, we used standard measures of labor inputs that show how the labor force is allocated between the domestic industries in the period. Those are compensation of employees, total employment, and hours worked. In order to analyse the composition of the labor force in each industry and country, we used labor quality indicators. We thus present a breakdown of the labor force and hours worked between skill levels and gender, as well as estimate the number of persons and hours worked in total employment which correspond to vulnerable employment situation.

All the socioeconomic indicators available in EXIOBASE 3 are presented in Table S7-1.

Table S7-1: Socioeconomic indicators in EXIOBASE 3

Code	Description
w01	Compensation of employees: low-skilled
w02	Compensation of employees: medium-skilled
w03	Compensation of employees: high-skilled
s01.a_m	Total employment: low-skilled male
s01.a_f	Total employment: low-skilled female
s01.b_m	Total employment: medium-skilled male
s01.b_f	Total employment: medium-skilled female
s01.c_m	Total employment: high-skilled male
s01.c_f	Total employment: high-skilled female
s02.a_m	Employment hours: low-skilled male
s02.a_f	Employment hours: low-skilled female
s02.b_m	Employment hours: medium-skilled male
s02.b_f	Employment hours: medium-skilled female
s02.c_m	Employment hours: high-skilled male
s02.c_f	Employment hours: high-skilled female
s03	Vulnerable employment
s04	Hours in vulnerable employment

Compensation of employees comprises wages, salaries, and employers' social contribution. For each country, this indicator was disaggregated from the National Accounts tables into 163 industries. It was used to disaggregate employment and hours worked into the EXIOBASE industries (for details see section 2 below). The total compensation of employees was estimated for three skill levels – low-skilled, medium-skilled, and high-skilled. The skill levels are detailed in section 3.

Sector-level data for total employment, paid employees, and hours worked were obtained by labor force surveys and industry surveys, collected from the International Labor Organization (ILO) and the Organization for Economic Co-operation and Development (OECD) databases (ILO 2013a, 2016; OECD 2014).

Total employment refers to total persons engaged in each industry. It covers both employees and self-employed persons. Employees are all persons with formal job attachment, even if in temporarily paid or unpaid leave. Self-employed persons include employers, own-account workers, members of producers' cooperatives, unpaid family workers at work, and persons engaged in the production of economic goods and services for own household consumption. In labor databases, employment can be given in both numbers of persons and of jobs. For EXIOBASE we decided to focus on the numbers of persons in work. It must be highlighted the fact that multiple job holders can correspond to more than 5% of employed persons (Lequiller 2004).

Persons in vulnerable working conditions are those with larger economic risks associated with their jobs. They are less likely to have formal arrangements, and are more at risks to economic cycles and environmental disasters. We use the ILO's definition of vulnerable employment, which comprises unpaid contributing family workers and own-account workers (ILO 2013b). We use workers without employee status as a proxy for vulnerable employment. We assume that most of workers that are not in formal paid employment, that is, are not classified as paid employees, are potentially in a vulnerable employment condition, especially those in developing countries.

Hours worked can be classified in four different types, which vary according to which hours are accounted for:

- *Hours actually worked* covers all types of workers, and relates to all the time that the persons spent on work activities during the reference period, whether paid or unpaid, but excluding time not worked, such as in annual, parental or sick leaves, public holidays, meal breaks, and commuter travel;
- *Hours paid for* include all hours paid for, whether worked or not. It comprises all paid leaves, and excludes hours not paid for, such as unpaid overtime;
- *Normal hours of work* covers only paid employees, and refers to hours of work established in agreements and labor regulation, and differ from hours paid for by excluding all overtime;
- *Hours usually worked* relates to average hours most commonly worked per week in paid and self-employment during a reference period, including usual paid and unpaid overtime.

The use of each category will depend on the aim of the research. For the purpose of EXIOBASE we consider *hours actually worked*, since it reflects the productivity of the industry, and are the usual output of hours worked in labor force surveys. While OECD Stats offer total hours worked for each industry, ILO gives average weekly hours worked by person for each sector. For hours worked in each industry in non-OECD countries, we multiplied average weekly hours by the number of persons employed and by 52 weeks.

When available, we use different weekly hours worked for total employment and for employees. Hours worked by persons in vulnerable employment for each year correspond to the difference between hours worked in total employment and those worked by employees. We used, however, same hours worked per week for male and female workers and per skill level.

2.2 Disaggregation of labor accounts into EXIOBASE classification

Labor inputs were disaggregated from broader economic sectors into the industry classification for EXIOBASE. That is because the aggregation level for labor statistics available from labor force surveys varied from 9 to 68 sectors, depending on the country. We adjusted the data in two steps.

First, we adjusted the time series to a same level of disaggregation. Data available for a same country were often available from different surveys, in different industry classifications (usually ISIC2, ISIC3 or ISIC4), throughout the time period. We disaggregated employment and employees data for all period based on the most detailed classification available. For that, we kept the data for the broad sector and estimated the distribution between the different sub-sectors as being the same as the first available year[1]. An example would be the disaggregation of the "Wholesale and retail trade and restaurants and hotels" from ISIC2 to the two separate sectors of "Wholesale and retail trade; repair of motor vehicles and motorcycles" and "Accommodation and food service activities" in ISIC4.

We then disaggregated the data from the most detailed classification available for each country into the industry classification for EXIOBASE. This step was done taking into reference the compensation of employees available from national accounts. It was assumed that, inside a same broad (less detailed) sector, all workers would earn similar hourly salaries and compensations, as well as work similar amount of hours. For example, for the "*pulp, paper and paper products*" broad sector from the labor statistics, which comprises the industries "*pulp*", "*re-processing of secondary paper into new pulp*" and "*paper*" in EXIOBASE, the total number of persons engaged was divided proportionally between the EXIOBASE industries according to their shares in total compensation of employees in the broad sector (eq. 1). This assumption was also applied for persons and hours worked in vulnerable employment.

$$\boldsymbol{e}_{i,b} = e_b^{data}\left(\boldsymbol{c}_{i,b} / \sum_i \boldsymbol{c}_{i,b}\right) \qquad (1)$$

Where:

$\boldsymbol{e}_{i,b}$ = Vector of total disaggregated employment in industry *i* within broad sector *b,* in EXIOBASE

e_b^{data} = Total employment in the broad industry sector *b*, from labor statistics

$\boldsymbol{c}_{i,b}$ = Vector of compensation of employees in all industry *i* belonging to broad sector *b*, in EXIOBASE

[1] In exceptional cases, the values were adjusted. That happened when there was a significant difference between two surveys which was not explained just by new classification of industries. These adjustments will be explained further in section 5.

2.2.1 Labor types: skill levels and gender

Labor inputs are divided for gender and skill types. We use three skill types (low-, medium, and high-skilled), based on occupations and educational attainment levels. For occupations, we use the definition from the *International Standard Classification of Occupations* (ILO 2012a) and, for educational attainment, the *International Standard Classification of Education* (UNESCO 2012). The correlation between the skill levels and occupations and education attainments is presented in Table S7-2.

Table S7-2: Correlation between skill types, occupations, and educational attainment levels

Skill type	Occupations	Educational attainment levels
Low-skilled	9 Elementary occupations	0 Less than primary education 1 Primary education 2 Lower secondary education
Medium-skilled	4 Clerical support workers 5 Services and sales workers 6 Skilled agricultural, forestry and fishery workers 7 Craft and related trades workers 8 Plant and machine operators, and assemblers	3 Upper secondary education 4 Post-secondary non-tertiary education
High-skilled	1 Managers 2 Professionals 3 Technicians and associate professionals	5 Short-cycle tertiary education 6 Bachelor's or equivalent level 7 Master's or equivalent level 8 Doctoral or equivalent level

We provide industry-level information on labor types for persons engaged and hours worked. We also present a breakdown of compensation of employees per skill level. The availability of such a level of detail of labor types reflects the heterogeneity of labor force and the differences in remuneration of workers.

The main source for gender and skill types information was labor force surveys, gathered from ILO LABORSTA and ILOSTAT databases. Though number of workers by skill type is often available from these surveys, they usually do not account for hours worked or wages. Therefore, we assume no distinction in hours worked per week for different skill types.

To calculate the distribution of compensation of employees, we use relative wages inside a sector. That means that the relative difference between wages for high- and low-skilled workers would be similar inside a broad sector, even if the absolute wages are not similar. Relative wages were calculated from earning and income surveys, collected from national statistics offices. The relative wages for skill types are considered to be the same for EXIOBASE 2 (Wood et al. 2015).

Due to the high aggregation level for these data, labor types were calculated as shares of total inputs. We assume that the distribution of skilled workers would not differ greatly among industries in a broad sector[2], and therefore, same distribution of gender and skill types can be applied inside a broad economic sector. It should be noted that, whilst for manufacturing sectors no skill data were available, the gender distribution was usually available. Table S7-3 presents the aggregate industry sectors for which labor types shares were calculated.

Table S7-3: Aggregated industries available for labor types

Code	Industry
A & B	Agriculture, forestry, hunting and fishing
C	Mining and quarrying
D	Manufacturing
E	Electricity, gas and water supply
F	Construction
G	Wholesale and retail trade
H	Hotels and restaurants
I	Transport, storage and communication
J	Financial intermediation
K	Real estate, renting and business activities
L	Public administration and defence; compulsory social security
M	Education
N	Health and social work
O	Other community, social and personal services
P	Private households with employed persons

2.2.2 Estimating labor in the Rest of the World

EXIOBASE 3 contains five rest of the world (RoW) regions: RoW Asia and Pacific, RoW Latin America and the Caribbean, RoW Europe, RoW Africa, and RoW Middle East. We also provide labor accounts for these regions. It is, however, important to highlight that labor estimations in the RoW regions are highly uncertain due to the assumptions used. As labor statistics are scarce for the different regions, most of the data were estimated.

For estimating labor accounts for these regions, we first estimated the total number of persons in employment for each of them. For estimating total employment, we used estimates from the ILO for total employment per broad sector (agriculture, industry, and services) for each region for the years 2000, 2007, 2010, and estimates for 2011 (ILO 2012b). Employment for the period 1995-1999 and for 2012 were estimated using the same growth rate as population for the region (The World Bank 2016). For the period between 2000 and 2007, and that between 2007 and 2010, it was estimated linear growth in employment numbers for each broad sector.

The ILO regions were aggregated into the EXIOBASE RoW regions and subtracted the data for the EXIOBASE countries. Then, a proxy country was used to estimate hours worked, labor types, and share of total workers in vulnerable employment in the three broad sectors. The proxy is an EXIOBASE country that represents an average closest to most populated countries in the rest of the region regarding

[2] Although there can be large differences among industries in the manufacturing sector, most of available information was highly aggregated for total manufacturing.

average share of women in non-agricultural sectors and educational attainment of the population (The World Bank 2016). The correlation between the EXIOBASE and the ILO regions, as well and EXIOBASE countries subtracted for each region and proxy country for labor hours, types, and vulnerable employment are presented in Table S7-4.

Table S7-4: Assumptions for Rest of the World labor accounts

Rest of the World Regions	Regions in ILO	EXIOBASE countries in the specific region	Proxy for labor types
RoW Asia and Pacific	East Asia Southeast Asia and the Pacific South Asia	Australia China India Indonesia Japan South Korea Taiwan	Indonesia
RoW Latin America and the Caribbean	Latin America and the Caribbean	Brazil Mexico	Mexico
RoW Europe	Central and South-Eastern Europe (non-EU) and CIS	EU28, Norway, Switzerland	Spain
RoW Africa	North Africa Sub-Saharan Africa	South Africa	South Africa
RoW Middle East	Middle East	Turkey	Turkey

2.3 Adjustments and further uncertainties

The main challenge to integrate labor data for the time series was the variety of industry classification and sources of labor data.

Industry classification varied from just 9 industries (top level ISIC rev.2) to 68 industries (moderately to highly detailed ISIC rev.4). Most data were available in two different classifications throughout the time series (ISIC rev.3 and ISIC rev.4), and thus had to be combined in one single classification. The disaggregation of older data into more detailed industry classification carries uncertainties regarding potential changes in industry classification throughout the time period. These assumptions also neglect potential structural changes in how labor distribution changes over time inside broad sectors.

Detailed data for labor in different manufacturing industries for most of the countries were only available, however, for paid employees and until 2008. For up to 2008, it was assumed that total employment followed the same distribution (a constant ratio of employees per total employment in the manufacturing sector). For data following 2008, a similar distribution of total manufacturing data for the latest year available was assumed.

Besides uncertainties regarding changes in industry classification throughout the time series, highest uncertainties come from different – and sometimes inconsistent – data sources. Main sources of labor data were national accounts questionnaires from national statistical offices and labor force surveys. However, various records come also from official estimates, population surveys, and establishment surveys. In cases of high inconsistency between labor data, we maintained the latest values, assumed to be more reliable, and estimated the past time series. The estimation of past values was based on past growth rates for each sector.

Missing data were estimated according to the closest available values for each sector. Gaps between know values were filled assuming a linear rate of change. In cases where either previous or subsequent values were unknown or highly inconsistent, data were estimated based on labor force growth. For estimating missing data on vulnerable employment a linear relationship to the share of employees in total employment was assumed.

With few exceptions, labor data had to be combined from different sources and classifications. Only seven countries presented a consistent industry classification throughout the entire time series. Table S7-5 summarizes the integration and estimated data for EXIOBASE countries throughout the time series.

Table S7-5: Combination of different industry classification and estimated data for throughout the time series for labor accounts

		EXIOBASE countries
Combination of different industry classifications	No combination	AT, BE, CZ, DE, FR, IT, RU,
	Two	AU, BR, CA, DK, EE, ES, FI, GB, GR, HR, HU, IN, IE, KR, LT, LU, LV, MT, MX, NL, NO, PL, PT, RO, SE, SI, SK, TW, US
	Three	BG, CH, CN, CY, ID, JP, TR, ZA
Estimated data	Estimated data from past growth rates (inconsistency in data sources)	BG, CN, ID, IE, LT, RU, TW, US, ZA
	Estimated missing data	BR, HR, CY, HU, IN, JP, LV, MT, MX, PL, ZA

Division in skill levels was also not available for the entire period and for all the countries. Data for skill level division per gender was only available until 2008. For years not covered, the same distribution of skill levels between genders and sectors from the closest year available was used, combining with known gender distribution for the year.

In general, data on employment quantity and quality have higher uncertainty in smaller sectors.

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Appendix B

Simas, M., K. Wiebe and R. Wood. 2018c. Mapping the structure of the global labour market: Developing fully harmonized labour accounts for MRIO analysis. *Unsubmitted manuscript.*

Awaiting publication and not included in NTNU Open

Appendix C

Simas, M., R. Wood, and E. Hertwich. 2015. Labor Embodied in Trade: The Role of Labor and Energy Productivity and Implications for Greenhouse Gas Emissions. Journal of Industrial Ecology 19(3): 343–356.

Labor Embodied in Trade

The Role of Labor and Energy Productivity and Implications for Greenhouse Gas Emissions

Moana Simas, Richard Wood, and Edgar Hertwich

Keywords:
consumption-based accounting
energy embodied in trade
factor productivity
industrial ecology
multiregional input-output analysis
trade footprint

Supporting information is available on the *JIE* Web site

Summary

Global production chains carry environmental and socioeconomic impacts embodied in each traded good and service. Even though labor and energy productivities tend to be higher for domestic production in high-income countries than those in emerging economies, this difference is significantly reduced for consumption, when including imported products to satisfy national demand. The analysis of socioeconomic and environmental aspects embodied in consumption can shed a light on the real level of productivity of an economy, as well as the effects of rising imports and offshoring. This research introduces a consumption-based metric for productivity, in which we evaluate the loss of productivity of developed nations resulting from imports from less-developed economies and offshoring of labor-intensive production. We measure the labor, energy, and greenhouse gas emissions footprints in the European Union's trade with the rest of the world through a multiregional input-output model. We confirm that the labor footprint of European imports is significantly higher than the one of exports, mainly from low-skilled, labor-intensive primary sectors. A high share of labor embodied in exports is commonly associated with low energy productivities in domestic industries. Hence, this reconfirms that the offshoring of production to cheaper and low-skilled, labor-abundant countries offsets, or even reverts, energy efficiency gains and climate-change mitigation actions in developed countries.

Introduction

Globalization is characterized by a rapid increase in the volume of trade and has thus spread the environmental, social, and economic impacts of the goods and services we consume throughout the world (Baiocchi and Minx 2010; Tukker et al. 2014). The environmental and resource implications of global supply chains have been a strong focus, in particular, the effect of consumption by affluent countries (e.g., Dittrich and Bringezu 2010; Dittrich et al. 2012; Lenzen et al. 2012, 2013; Duchin and Levine 2013; Kanemoto et al. 2014). Social issues, including employment and labor conditions, are also important concerns. Production for export generates employment and hence income. Inadequate salaries, forced and child labor, and poor working conditions, as noted in the tragic accidents in Bangladeshi garment factories in April 2013 (BBC 2013), can, however, also be perceived as negative consequences of the globalization of supply chains (Fung 2001; Brown and O'Rourke 2007; Klassen and Vereecke 2012). Differences in the cost of labor have been a key driver of globalization. The multidimensional nature of environmental and social impacts resulting from offshoring labor hence forms an interesting backdrop to the globalization debate. We present a novel investigation of the employment connected to the production of internationally traded goods and explore the connection between employment and energy use embodied in trade and its implication to greenhouse gas (GHG) emissions. We specifically address

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the European Union (EU)'s trade with the external world and evaluate the origin of energy and labor embodied in imported products.

Although the decoupling of domestic energy consumption and GHG emissions from gross domestic product (GDP) can be the result of cleaner, more-efficient technologies, it can also mean that resource- and energy-intensive industries are being displaced to other countries. Hence, emissions are not reduced, but relocated (Ahmad and Wyckhoff 2003; Peters and Hertwich 2008a; Tukker et al. 2013). These impacts can be even further magnified if production shifts to countries with carbon-intensive energy mix or less-energy-efficient technologies—in this case, emissions would not only be reallocated, but could also increase. We hence shift productivity analysis from a territorial perspective, where improvements can occur unilaterally and at the expense of developing nations, to a consumption perspective, thus showing gross improvements irrespective of national borders.

Trade Theory

The availability and cost of factors of production will determine the shift in production between countries. Early trade theory, developed by Heckscher (1919) and Ohlin (1933) and later mathematically complemented by Vanek (1968), addresses the direction of trade flows between factor-abundant and -scarce countries. According to the Hecksher–Ohlin–Vanek (HOV) theorem, a capital-abundant country tends to produce and export capital-intensive goods and services and import labor-intensive ones. The opposite would occur to a labor-abundant country. Vanek's work emphasized that traded goods are a veil, and the HOV theorem is about the trade of the underlying factors of production, in that case, labor and capital (Fisher 2011). Although specific assumptions of the HOV theorem—identical consumption patterns among countries, identical technology and techniques, internationally equal prices of goods, and inexistence of trade barriers and additional costs of mobility—are criticized as unrealistic, the theorem provides valuable insights into the direction of net flows of factors embodied in trade. Ruffin (1977) argues that, with constant world demand for goods, country specialization would support the direction of the net trade flows, for at least one country is driven to production specialization according to its factor-abundant requirements.

Work by Leontief (1953, 1956) showed that, paradoxically, despite being a capital-abundant economy, the U.S. exports in 1947 were far more labor intensive and less capital intensive than imports in the same year. However, Leontief's paradox has been criticized later for neglecting the level of skills required to produce imported versus exported products. Studies showed that, despite being labor intensive, exports were high-skilled abundant and low-skilled scarce. Productive and skilled work, argued Maskus (1985), has higher share of capital embodied than low-skilled labor. Cörvers and de Grip (1997) analyzed 14 industrialized economies and concluded that capital-intensive economies have higher demand for high-skilled labor and knowledge-intensive human capital, a conclusion shared by Nishioka (2013). In that context, Leontief's results would not be as paradoxical as first thought and would rather complement the human capital approach to the HOV theorem. Two other explanations were offered to explain the paradox. The first one is the labor-capital ratio of trade. Factor intensity, in this approach, should be considered not as absolute factors embodied in net exports, but relative factors embodied in trade compared to those embodied in domestic production (Leamer 1980). The second is that the assumption of similar technology and productivities to calculate labor and capital embodied in imports (domestic technology assumption) leads to false quantification of real factors used in their production. When using real trade data and productivities from the trade partners' input-output (I-O) tables (IOTs) and considering domestic share of factors embodied in supply chains of imported goods, the paradox does not hold (Reimer 2011).

Lai and Zhu (2007) tested bilateral trade between 41 developed and developing countries and concluded that factor abundance will likely affect bilateral net trade flows, especially among countries with larger endowment differences, but will not necessarily maintain when comparing trade between two capital-abundant economies. For the latter, technological differences are more important predictors for the net trade direction than the HOV factor endowment differences. Hakura (2001) uses I-O data to test the HOV model in the European Community and infers that allowing technology differences in the model can give a better picture of net factors embodied in exports. However, even using several individual regions' I-O data, intermediate inputs are still not traceable. By using intermediate input matrices, Reimer (2011) and Nishioka (2013) highlight the importance of tracing the regional origin of inputs and production stages, which can be achieved by using a consumption-based analysis through a multiregional input-output (MRIO) approach. The researchers complement the conclusion of production specialization by Ruffin (1977), but determine that countries do not specialize in products, but in particular stages of the production process for which the country has the lowest opportunity cost.

Energy and Labor

Two of the key factors of production are labor and energy. Energy, as opposed to labor, is mobile, but is increasingly becoming subject to environmental constraints in certain regions. Labor costs meanwhile play an important role in labor-intensive industry outsourcing and offshoring (Grossman and Rossi-Hansberg 2008). One of the direct effects of this phenomenon is the shift of unskilled labor-intensive stages of production toward unskilled labor-abundant countries, usually developing ones, whereas more technologically advanced stages remain in countries abundant in skilled labor (Feenstra 2007; Foster-McGregor et al. 2013; Nishioka 2013). Alsamawi and colleagues (2014) quantified the flow of labor and wages embodied in international trade and showed that, whereas the highest flows of labor hours are embodied in exports from developing to developed countries, major flows of wages are embodied in trade between developed economies.

Labor conditions in developed countries, mainly countries in the Organisation for Economic Cooperation and Development (OECD) region, can be significantly different from those in developing countries. Though there are generally good working conditions in developed countries, both emerging economies and less developed countries have a large pool of unemployed or underemployed persons. Vulnerable employment can reach up to 85% in Sub-Saharan Africa, compared to a world average of 50% and less than 10% in developed countries. Child labor is still a problem in several developing countries, there are barriers to labor market participation for youth and women, and there are high working poverty rates (average 40% of laborers in the world are working poor, virtually all of them located in developing countries) (ILO 2008). Job creation, especially when divided by skill level and region where the employment is created, can therefore act as a proxy for potential social impacts of consumption and trade.

Studies of emissions embodied in international trade have been conducted in response to the increasing discussions on emissions responsibility and the role of international trade of goods and services in climate change mitigation. Those consumption-based studies use MRIO models. For a recent review of MRIO developments and applications, refer to Tukker and Dietzenbacher (2013). MRIO-based studies of the interaction between trade and environment include GHG emissions embodied in trade and its implications for climate policy (e.g., Hertwich and Peters 2009; Minx et al. 2009; Peters and Hertwich 2008b; Kanemoto et al. 2014; Peters et al. 2011), pollutants and other environmental impacts embodied in trade (e.g., Tukker et al. 2013; Lenzen et al. 2012, 2013), and land-use or ecological footprints and resource consumption (e.g., Ewing et al. 2012; Galli et al. 2012; Giljum et al. 2008; Hoekstra and van den Bergh 2006; Weinzettel et al. 2013). Nonetheless, empirical analyses of global socioeconomic impacts of international trade are scarce (Timmer et al. 2012; Foster-McGregor et al. 2013; and the recently published The Labor Footprint of Nations by Alsamawi et al. [2014]). Frequently, studies focus on international trade's effects on domestic labor (see, e.g., Alcala and Ciccone 2004; Feenstra and Hanson 1996; Feenstra and Hong 2010; Gu and Rennison 2005; Lee and Schluter 1999; Ben Salha 2013).

Our starting point is the hypothesis that developed countries would have higher energy content in exports, compared to labor, than that of developing countries, and we expect to see disparate labor and energy productivities around the world. This study takes a unique look into the trade-offs involved in energy and labor footprints of trade, complementing previous work on environmental footprints with an investigation of employment footprints. To our knowledge, it is the first study to compare energy and labor productivities while investigating the transfer of energy and labor that is embodied in trade, in particular, for European consumption. This is also one of the first articles to investigate flows of employment embodied in trade focusing on the origin of those jobs, together with the recently published article by Alsamawi and colleagues (2014). This research introduces a consumption-based metric for productivity, in which we evaluate the loss of productivity of developed nations resulting from imports from less-developed economies and offshoring of labor-intensive production. We expect to see a clear link between the energy and labor productivities and the development stage of the countries, and that this difference would be attenuated when a consumption-based approach is used. We estimate a loss in both energy and labor productivities for developed countries when accounting for imports for domestic consumption.

The remaining parts of the article are structured as follows. The next section presents the data structure and methods for productivity and footprints calculations, followed by the description of the results obtained for difference in productivities in a consumption-based approach, energy intensity of labor for different countries, and labor and energy footprints for the European Union (EU). The last two sections discuss the results and implications of energy and labor productivities to climate change contribution and give final remarks on the main findings.

Methods

We used a fully integrated MRIO model to calculate national production- and consumption-based productivities and footprints of international trade for the EU. A detailed description of the method and equations used and a background on I-O and MRIO analysis can be found in supporting information S1 on the Journal's website.

Productivity Accounting

Productivity is usually considered as a characteristic of the territorial production in a region. It measures the economic output per unit of production inputs required. Here, we focus on labor, energy, and GHG emissions. A country's productivity (p) will differ accordingly to the overall efficiency of industry, the composition of the domestic economy, and the methodological approach. We define territorial-based (TB) productivity as GDP per domestic factor requirements (R). We account thus for the sum of GDP of domestic industries, that is, value added created in domestic industries (v), plus taxes (t) and excluding subsides (s), as shown by equation (1):

$$p_{TB} = \frac{v + t - s}{R} = \frac{GDP}{R} \tag{1}$$

In a global economy, when offshoring of manufacturing stages occurs at increasing rates, TB productivity may offer only a competitive comparison between regions. One country's increase in productivity may come purely at the expense of offshoring production to a country with less regulation or lower labor costs, providing no net societal benefit across regions. Consumption-based accounting allows a more egalitarian approach to capturing the impacts of achieving a certain lifestyle. Based on the concept of allocation of life cycle and upstream supply-chain impacts to final goods and services consumed, it is used to evaluate the total impacts of lifestyles (Peters and Hertwich 2006; Wiedmann 2009). Based on discussions on consumption-based national GHG inventories (Peters 2008; Peters and Hertwich 2008a), we introduce a new measure to productivity accounting, by incorporating a consumption-based (CB) approach. CB productivity measures the requirements to satisfy domestic demand, considering the final consumption of domestic and imported products by households, governments, and gross capital formation. It offers a perspective for assessments of average global and regional impacts of domestic policies and lifestyles. We define it to differ from TB productivity by considering not GDP, but gross national expenditure (GNE). It accounts, then, for expenditure in domestic final demand ($\mathbf{y}^{rr}$) plus expenditure in imported goods and services consumed in final demand in country r ($\mathbf{e}^{sr}$), divided by country r footprint (F). Footprints are calculated by multiplying total (direct plus indirect) requirements for production of goods and services in countries of origin (M) by the consumed products, as shown by equation (2):

$$p_{CB}^{r} = \frac{y^{rr} + \sum_s e^{sr}}{(M^r y^{rr} + \sum_s M^s e^{sr})} = \frac{GNE}{F} \tag{2}$$

The difference between these two approaches allows identifying the differences between factors of production allocated toward exports and those required for domestic consumption. Although the difference cannot correlate directly to net importers or exporters of embodied factors in trade, it can incorporate offshoring of energy- and labor-intensive industries to overall productivity. Wiedmann and colleagues (2013) offer a different adjustment to TB productivity by looking at GDP per factor footprint F. Though this clearly includes the consumption-based approach for environmental impact, it includes impacts of imports and excludes impacts of exports in the footprint denominator, whereas the opposite (inclusion of exports, exclusion of imports) is included in the GDP numerator. Hence, Wiedmann and colleagues (2013) are still looking at the efficiency of supply, whereas we are looking at the efficiency of demand.

Energy Intensity of Labor

We evaluate whether the HOV theorem applies, by employing a simplification of the relative intensities, as proposed by Leamer (1980), to the countries studied. We evaluate whether labor-intensive economies specialize in the export of labor-intensive goods, that is, with higher content of labor compared to energy. We take the domestic production of domestically consumed goods (y^{rr}) as a proxy for a country's endowments as labor or energy abundant. For that, we calculate the energy intensity of labor, or the energy (E)/labor (L) ratio, of total domestic consumed production (y). The same calculation is applied to imported (m) and exported (e) goods. We evaluate whether there is a relation between energy intensity of labor for domestic, exports, and imports and GDP per capita (equation 3).

$$EIOL_y = E_y/L_y \tag{3}$$

We are also interested in verifying whether the augmentation of labor TB productivity by increasing energy use, as proposed by Cleveland and colleagues (1984) and Eisenmenger and colleagues (2007), is correlated to the development stage, as proposed by previous studies on socioecological transitions (Fischer-Kowalski et al. 2012). The energy intensity of labor has been used to analyze socioeconomic systems (as "exosomatic metabolic rate") quantifying the energy (converted outside the human body) used to amplify the output of useful work. This rate is usually quantified by energy per time (joules per hour) (Eisenmenger et al. 2007; Giampietro et al. 2013). We use the same concept of energy per labor, but the latter is quantified in persons-year equivalent(p-y_{eq}).

Footprints of Trade and Data Source

The footprint of the trade between regions was calculated as the difference of footprints of exports and imports, resulting in total net exports. If the balance is positive, the region is an exporter of labor, energy, or GHG emissions. As a result, domestic consumption in the region has lower upstream factor requirements than factor utilization for domestic production. Likewise, negative balances indicate that the region demands more factors than those available domestically. For the trade between EU and other regions, only products leaving and entering the EU are counted in the trade balance, and flows inside the region (e.g., from France to Italy) were considered as domestic.

We used EXIOBASE v.1 (Tukker et al. 2013) to model both factor productivity and trade footprints. The EXIOBASE v.1 MRIO model represents the world economy in the year 2000 as the production and consumption of 129 products by 129 industries and seven categories of final demand in 43 countries (27 EU and 16 non-EU: United States, Japan, Canada, South Korea, Australia, Switzerland, Taiwan, Norway, China, Brazil, India, Mexico, Russia, Turkey, Indonesia, and South Africa) and a rest of the world (RoW) region. Through applying known GDP growth factors to final demand, the model was forecast to 2007. Nonetheless, the coefficient (A) matrix is assumed to be static. Thus, gains in productivity between 2000 and 2007 were not taken into account, and productivity measures are based in 2000 technology. We used the industry-by-industry model, and values are represented in 2007 euros. Monetary flows, net energy use, and GHG emissions were taken from EXIOBASE. Monetary data sources originated from national accounts and published supply-and-use tables and IOTs for each country. Energy use was obtained from the International Energy Agency and emissions were calculated for both energy and nonenergy use, based on level of activity (e.g., consumption of fossil fuels [FFs], number of cows, and tonnes of cement produced) and correspondent emission factors. Primary sources for labor input were national labor force surveys, gathered from the International Labor Organization (ILO) LABORSTA database (ILO

2010), and a combination of labor force and industrial surveys in national accounts, obtained from the OECD's STAN database (OECD 2011). The 2007 labor estimates are the basis for the update of labor accounting for EXIOBASE (from version 1 to version 2) to 2007 in the EU-FP7-funded project, CREEA.

Results

Global Energy and Labor Productivities

The difference in productivity from TB to CB approaches for labor and energy are illustrated in figure 1, and elasticities of productivity as a function of GDP per capita, calculated by regression analysis, are shown in table 1. A pattern for both labor and energy productivity according to GDP per capita is apparent. Detailed productivity for each factor is found in supporting information S2 on the Web. Countries with lower GDP per capita, represented by lower-income countries in the EU (EU-3; diamonds; see list of countries in supporting information S1 on the Web) and developing countries (DC; inverted triangles), have lower energy *and* labor TB productivity, at the same time that higher GDP per capita countries, represented by middle- (EU-2; squares) and high-income countries in the EU (EU-1; circles), and high-income OECD countries (HI; triangles), tend to have higher TB productivities. This pattern may be explained by various causes. First, high-income countries tend to have more-energy-efficient technologies (Painuly et al. 2003), increased labor costs, and are increasingly specializing in activities that require high-skilled workers (Timmer et al. 2012).

Second, high-income countries tend to be specialized in the production of products and services with higher value added and lower labor and energy intensity; at the same time, they are usually dependent on imports of primary products and manufactured goods with lower value added. The second reason becomes explicit when international trade is internalized in the productivity measure. Although the tendency for correlation between productivity and GDP per capita is maintained, the difference between the regions is reduced, bringing the CB productivity levels of high-income countries closer to those of lower-income countries. It can be also noted that elasticities for GHG emissions present a better correlation with GDP per capita than energy use.

The difference in prices of the same products across countries poses a challenge for total productivity analysis. Exchange rates are determined by the prices of products that are traded internationally, not those predominantly consumed domestically. Because MRIOs are constructed using market exchange rates, differences in prices of products can insinuate a false difference in productivities. Ideally, price corrections should be used to assess economic productivity, but these are not possible because price data on products is unreliable or lacking. We present results for purchasing power parity (PPP) (The World Bank 2013) adjusted GDP as a compromise solution. Note, however, that this implies adjusting exports by a measure reflecting the price paid by consumers domestically.

Energy Intensity of Labor

According to Fischer-Kowalski and colleagues (2012), though developed countries have completed their historical socioecological transition—from agrarian regimes energetically based upon land use to industrial regimes based upon FFs and a variety of modern energy conversion technologies—several emerging economies are still going through this transition. There is, however, a substantial difference on the paths of these transitions for developed and developing countries. Whereas the first group is usually characterized by economies in which domestic agricultural development generated surplus that were then invested in other sectors, several developing countries are confronted with a context of integration in a global economic system, where the international division of labor strongly influences the transition process and production specialization, especially from the end of the twentieth century. In South Asia and South America, for example, industrial development was not financed by agricultural value-added surplus, but by international private investments and loans from development banks, aimed primarily to promote integration into the world market and enlarging export-oriented production (Eisenmenger et al. 2007).

In a socioecological transition, not only energy source and conversion technologies change, but also the organization of society, which includes the economic system, demography, settlement patterns, and social relations. In this context, labor goes through substantial changes. This transition implies the substitution of physical work by human and draught animals for modern energy sources, mainly electricity and FFs, which leads to the increase of energy use to augment labor productivity.[1] This has been shown by empirical studies of the U.S. economy (Cleveland et al. 1984; Hall et al. 1986). Wealth growth thus would be achieved mainly from gains in labor productivity, through the efficient use of modern energy sources, and not only from an increase in labor force. At the same time, physical labor gives way to intellectual labor as agricultural production shifts to manufacture and then to services, requiring higher skills (Fischer-Kowalski et al. 2012; Schandl et al. 2009).

We would expect, then, to see a shift from labor- to energy-intensive production. Following the assumptions of Leamer (1980), developed countries should exhibit a higher input of energy, relative to labor, than developing regions. That would apply to both domestic production and, especially, to exports. Figure 2 shows the energy intensity of labor of the domestic economy (domestic production, excluding exports; left) and exported (middle) and imported (right) products and services for the 43 countries and the RoW region, grouped according their GDP per capita. This figure shows a pattern of increasing use of energy per unit of labor in domestic production with increasing GDP per capita, and even a more noticeable one for exported-oriented production. In terms of the HOV theorem, affluent countries act as if they had a high endowment of energy, whereas less-affluent countries act as if they had a high endowment of labor. That would suggest that, on average, developing countries are labor-intensive products exporters, whereas

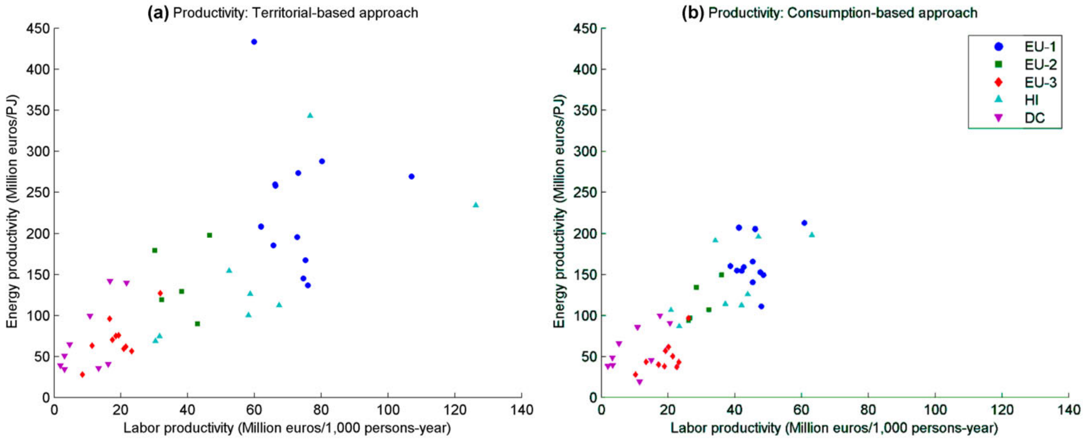

Figure 1 Difference in energy-labor productivity from the territorial-based approach (a) to consumption-based approach (b). PJ = petajoules; EU = European Union; EU-1 = high-income countries in the EU; EU-2 = middle-income countries in the EU; EU-3 = lower-income countries in the EU; HI = high-income OECD countries; DC = developing countries.

Table 1 Elasticity for territorial- (TBP) and consumption-based (CBP) productivities of labor, energy, and GHG emissions as a function of GDP per capita (left) and GDP PPP per capita (right)

	GDP per capita				*GDP PPP per capita*			
	TBP		*CBP*		*TBP*		*CBP*	
	ε	R^2	ε	R^2	ε	R^2	ε	R^2
Labor	0.94	0.97	0.73	0.95	1.33	0.94	1.05	0.93
Energy	0.52	0.63	0.47	0.61	0.67	0.51	0.62	0.50
GHG emissions	0.61	0.66	0.56	0.67	0.80	0.55	0.74	0.56

Note: GDP = gross domestic product; PPP = purchasing power parity; TBP = territorial-based productivity; CBP = territorial-based productivity; GHG = greenhouse gas; ε = elasticity for productivity as a function of GDP per capita; R^2 = R-squared, or coefficient of determination.

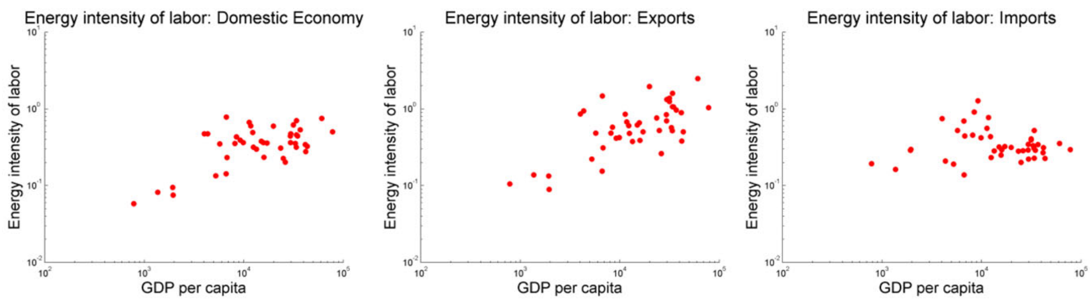

Figure 2 Energy intensity of labor, in terajoules per persons-year equivalent, as a function of GDP per capita for production for total national economy (left), exported products (middle), and imported products (right). GDP = gross domestic product.

developed countries are energy-intensive products exporters. Surprisingly, we do not identify a discernible pattern regarding the energy intensity of labor of imported products. A decomposition of energy/labor ratio into industries and elasticities is available in supporting information S2 on the Web.

Labor Embodied in Trade

Globally, employment associated with the production of goods and services in international trade, both to intermediate and final consumption, was of 560 million persons-year equivalent. That corresponds to approximately 18% of total

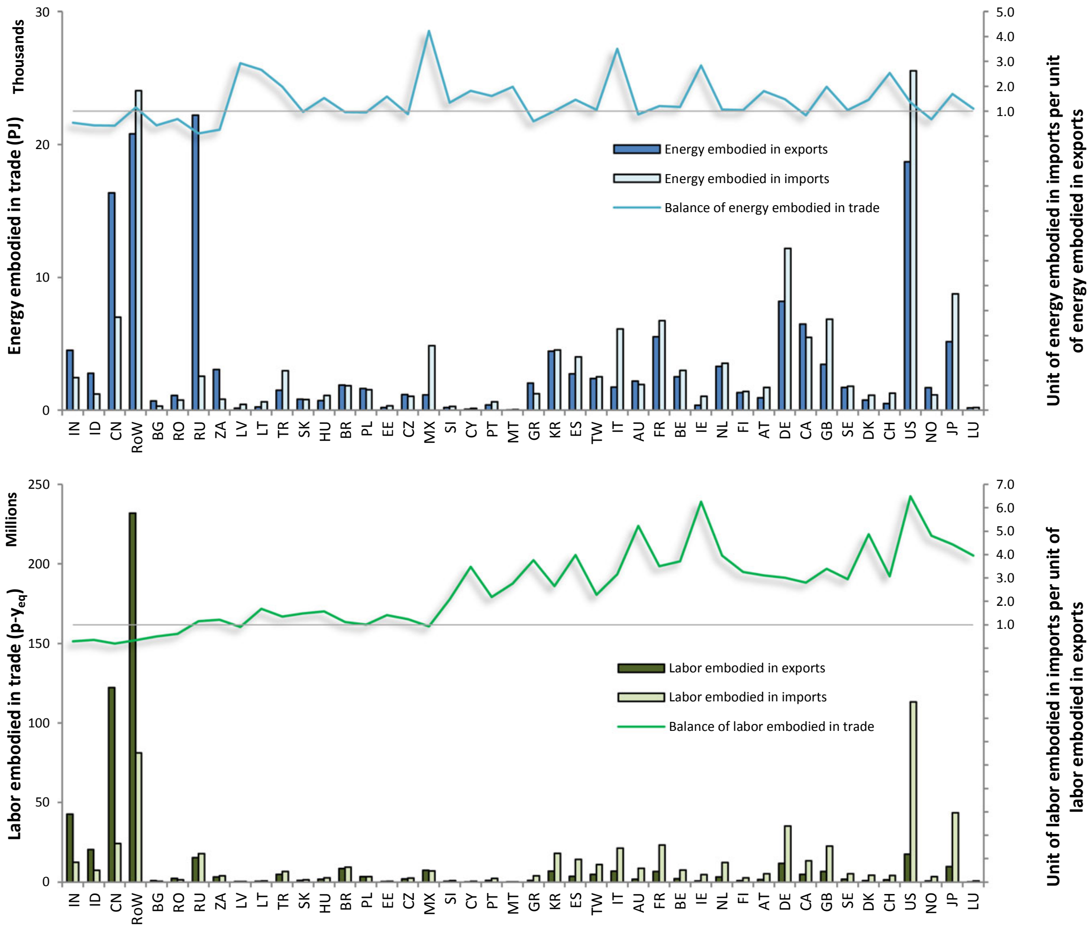

Figure 3 Energy and labor embodied in imports and exports (bars) for the 43 countries and the rest of the world, organized according to their gross domestic product per capita. The line shows the unit of energy and labor embodied in imports per unit of energy and labor embodied in exports (right axis). PJ = petajoule; p-y$_{eq}$ = persons-year equivalent.

employment and is somewhat lower than compensation of employees and value added embodied in international trade of 22% and 23%, respectively. Differences between share of employment and compensation of employees embodied in trade reflect differences in skills and wages. Disparities in wages are significant between high- and low-skilled employees in developed and developing countries. The latter was demonstrated by Alsamawi and colleagues (2014). Wages differ significantly not only among skill levels within the same country, but also the same skill level in different countries.

The share of employment embodied in trade is significantly lower than that of energy displaced through international supply chains, which is 35%. Energy use from FF combustion embodied in traded products corresponds to 31% of total fossil energy consumption globally and almost three quarters of all energy embodied in trade. Figure 3 displays energy and labor embodied in imports and exports for each of the countries assessed (in bars). The line in the figure indicates labor and energy embodied in imports per unit embodied in exports. Factors embodied in imports and exports differ significantly. In the case of energy, imports can account for 4.2 times the amount of energy embodied in exports, in the case of Mexico; for labor, the highest rate is for the United States (6.5 times). The profile for net imports of embodied energy is not clearly related to GDP per capita, whereas it can be observed that all high-income countries are net importers of labor.

Labor, Energy, and Greenhouse Gas Footprints of the European Union's Trade

Table 2 indicates that, in 2007, the EU was a net exporter, in monetary trade, for most industries, but the same did not

Table 2 Net trade volume and balance of factors of production embodied in the EU's trade

	Balance of trade			
	Trade volume (MM €)	*Embodied labor (1,000 p-y_{eq})*	*Embodied energy (PJ)*	*Embodied emissions (Mt CO_2-eq)*
Agriculture, forestry, and fishing	(−12,829)	(−45,854)	(−178)	(−105)
Mining of energy materials	(−166,437)	(−2,387)	(−3,256)	(−229)
Other mining and quarrying	(−21,472)	(−1,247)	(−395)	(−10)
Food and tobacco	25,906	(−723)	(−33)	(−7)
Textiles, wearing apparel, and leather	(−28,397)	(−5,258)	(−225)	(−10)
Wood and paper products	18,043	(−1,245)	(−175)	(−6)
Fuel products	(−7,165)	(−367)	(−1,126)	(−41)
Chemical products	103,703	(−1,880)	(−2,245)	(−83)
Nonmetallic mineral products	14,508	(−1,144)	69	(−3)
Metal products	23,074	(−1,283)	(−1,691)	(−171)
Electric and electronic equipment	110,170	(−4,844)	(−535)	(−3)
Transport equipment	69,927	(−465)	43	1
Other manufacturing	17,998	(−1,458)	(−794)	(−30)
Energy and water	(−4,242)	(−1,004)	(−3,495)	(−437)
Construction	(−1,507)	(−451)	(−69)	(−5)
Trade, hotels, and restaurants	(−40,551)	(−15,156)	(−292)	(−16)
Transport and communication	(−28,576)	(−11,133)	(−1,863)	(−74)
Other services	(−39,369)	(−22,837)	(−530)	(−79)
Total	**32,786**	**(−118,737)**	**(−16,791)**	**(−1,307)**

Note: EU = European Union; MM € = million euros; p-y_{eq} = persons-year equivalent; PJ = petajoule; Mt CO_2-eq = megatonnes of carbon dioxide equivalent.

apply for embodied labor, energy, or emissions. Most of the net imports into the EU concentrate in the sectors of Mining of energy materials, Textiles, wearing apparel, and leather, Other mining and quarrying, and Agriculture, forestry, and fishing. This shows how dependent the EU is on primary products and textiles. Nonetheless, embodied energy, emissions, and labor are not concentrated only in those sectors. The difference between monetary balance and factors of production embodied in trade can be mainly a result of two different aspects.

For a number of sectors, for example, Electric and electronic equipment and Metal products, the EU is a net exporter in terms of value, but a net importer in terms of labor, energy, and/or GHG. Difference in productivity can be one of the explanations for this pattern. Developed countries, as discussed previously, have higher TB productivity for both energy and labor. Nevertheless, it may not be the only reason for this.

As brought by the HOV theorem, production specialization and offshoring of labor- and energy-intensive industries and manufacture stages can also explain the difference in the balance of monetary and factors of production inside a broad sector. Industry aggregation leads to loss of detail in obtained results and has been thoroughly discussed in Su and colleagues (2010) and Lenzen (2011). When expanding the table to the EXIOBASE disaggregation level (table S2–2.13 in supporting information S2 on the Web), the difference between products in a same sector shows that, though overall trade balance is positive, the difference might be in the products traded: Products with higher value added and lower energy intensity are exported, and products with low value added and/or higher energy intensity are imported. That is the case for the Metal products sector, where significant amounts of energy and emissions are embodied in aluminum imported into the EU, at the same time that most exports from this industry consists of fabricated metal products, which have higher value added and lower energy requirement. Nevertheless, even at the level of detail offered by EXIOBASE, aggregation may lead to uncertainties in the analysis.

Important to understanding the difference between trade and embodied factors are the origin and destination of net imports and exports. Figure 4 shows the balance of the EU's trade with other countries broken down by grouped industries for each of the indicators investigated: (a) monetary trade; (b) labor; (c) energy; and (d) GHG emissions. Detailed tables for imports, exports, and net factors embodied in trade between the EU and other regions can be found in tables S2–2.1 to S2–2.12 in supporting information S2 on the Web.

By separating embodied energy, labor, and GHG emissions by product and country of origin/destination, hotspots of impacts resulting from European consumption could be identified. Most of the net imports of energy come from energy-intensive activities in Russia, especially from mining of energy materials, energy and water production and distribution, transport and communication, metal products, chemical products, and fuel products. Energy embodied in the EU's imports from the RoW is mainly the result of mining of energy materials. Russia also contributes to most of the net embodied emissions, mainly

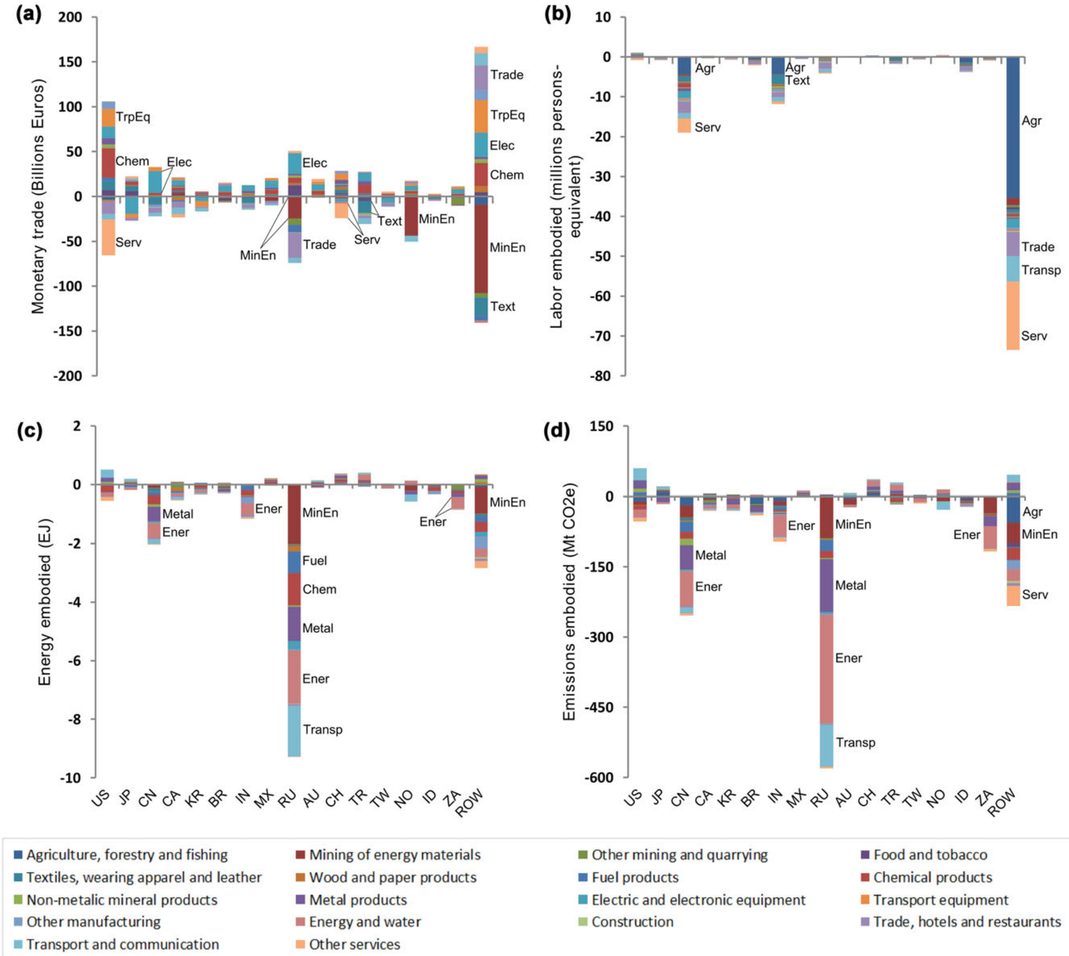

Figure 4 Factors of production embodied in the EU's net trade divided by country and industry: (a) net monetary trade, in billion euros; (b) labor embodied in trade, in million persons-year equivalent; (c) energy embodied in trade, in EJ; (d) GHG emissions, in million tonnes CO_2-eq. Legend in figure: Agr = Agriculture, forestry, and fishing; Chem = Chemical products; Elec = Electric and electronic equipment; Ener = Energy and Water; Fuel = Fuel products; Metal = Metal products; MinEn = Mining of energy materials; Serv = Other services; Text = Textiles, wearing apparel, and leather; Trade = Trade, hotels, and restaurants; Transp = Transport and communication; TrpEq = Transport equipment. EU = European Union; EJ = exajoule; GHG = greenhouse gas; Mt = megatonnes; CO_2-eq = carbon dioxide equivalent; p-y_{eq} = persons-year equivalent.

through products from the sectors of energy and water, metal products, transport and communication, and mining of energy materials. China, India, and South Africa gain importance in embodied emissions resulting from their energy mix, mostly coal based, and most of the emissions embodied in products imported from these countries occur in electricity production. The impacts take place in those industries by direct or indirect effects of the EU's imports, and not necessarily the products imported by the EU.

As a result of the large differences in labor TB productivity among countries, jobs occupied elsewhere to satisfy the EU's demand are significantly higher than labor employed in the EU for producing exported products. Most of the labor embodied in the EU's imports comes from the RoW, China, India, Russia, and, to a lesser degree, Indonesia and Turkey. Although net imports of labor were expected to be high from developing countries, the share of labor embodied from the RoW was surprisingly significant, accounting for over 50% of all labor

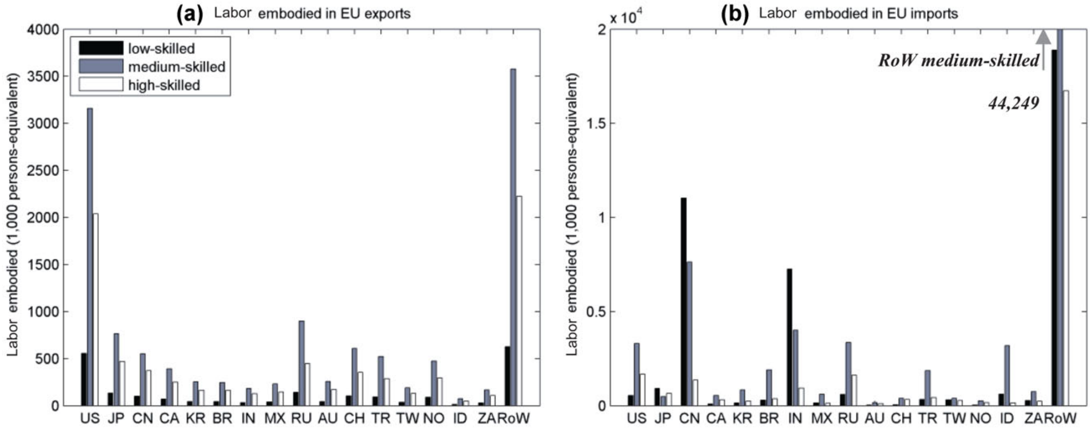

Figure 5 Labor embodied in the EU's exports (a) and imports (b), divided by country and skill level. EU = European Union; RoW = rest of the world.

embodied in the EU's imports. Almost half of labor embodied in imports from the RoW come from Agriculture, fishing, and forestry (44%), whereas services account roughly for the other half (42%). The RoW region, which comprises approximately 200 countries, is only responsible for approximately 10% of the global GDP, although it has a significant role for embodied labor. First, because of its contribution to the EU's trade: 28% of the EU's imports and 30% of exports. Second, because of its high labor intensity: The region comprises nearly one third of the world's total employment. Despite the high figures, only approximately 8% of total employment in the RoW is caused by the production of products exported to the EU.

Besides the critical difference between the amount of labor imported to and exported from the EU, the difference in the quality of these jobs is also noteworthy. Approximately 50% to 55% of both imported and exported labor embodied in the EU's trade comprises medium-skilled jobs. The difference in job quality is that, whereas over 30% of jobs dedicated to the production of exported products in the EU are composed by high-skilled positions, the same proportion is occupied by low-skilled labor elsewhere to supply the EU's consumption—44% of which in India and China and 45% in the RoW, as illustrated in figure 5. Even though the EU has 6 times as much employment embodied in imports as in exports, compensation of employees associated with imports corresponds to only 0.9 that associated with exports. The difference between high-wage, high-skilled labor embodied in exports and low-skilled labor embodied in imports is consistent with previous studies on human capital embodied in net trade flows concerning wages, productivity, and skill level (Nishioka 2013; Cörvers and de Grip 1997; Maskus 1985; Timmer et al. 2012; Foster-McGregor et al. 2013).

Discussion

Our study was a first attempt to quantify the relation between social and environmental impacts from the consumption perspective in order to look at drivers and impacts of development and associated globalization. We provided a global analysis of flows of embodied energy and labor while also focusing on the impacts of the European lifestyle. Although Europe is a net exporter for value added (see also Johnson and Noguera 2012), it is a net importer for all of the factors assessed.

Productivity and Development Stage

Requirements and impacts of industries differ substantially among countries. Industry efficiency—regarding energy and labor requirements—is only one variable. Costs of production are becoming increasingly important to maintain competitiveness of several industries, especially those that rely on resource- and energy-intensive processes. Both imports and offshoring of production seek countries with lower costs per unit produced, rather than lower impacts. We confirmed that labor-abundant countries, that is, countries with lower energy intensity of labor of domestic production, specialize in the production and export of labor-intensive goods and services, as predicted by the HOV theorem. In a scenario with growing reallocation of production chains in search of minimizing costs and avoiding labor and environmental regulations, offshoring and outsourcing labor-intensive stages of production may lead to higher environmental impacts. That happens because labor-abundant countries generally have low energy TB productivity, and even lower TB productivities measured in terms of GHG emissions. Globalization causes a decrease of consumption-based energy productivity of developed countries, consequently leading to carbon leakage. Carbon leakage describes either a phenomenon of increased GHG emissions in developing countries as a result of climate policy in developed countries (strong carbon leakage) or a phenomenon of increasing net emissions embodied in imports to developed countries without an implied causal relationship to climate policy (weak carbon leakage) (Peters and Hertwich 2008b; Antimiani et al. 2013).

Most economic growth happens in emerging economies. Even though these countries have lower energy requirements per worker, they have higher requirements of both energy and labor per unit of GDP. Lower labor costs in developing countries lead to an increase of exports from labor-intensive industries of these countries.

Footprints of the European Union's Consumption

Most of the labor embodied in the EU's net imports comes from developing countries. Labor-intensive sectors, such as agriculture and services, account for most of the employment embodied in the EU's net imports, and most of the embodied labor comprises low and medium skilled. The labor footprint of the EU's trade shows great discrepancy between intensity and quality of jobs created in the EU for exports and those created elsewhere to supply products and services to satisfy European demand.

The assessments of the footprints of the EU's trade showed that the region is highly dependent on primary products, mainly from developing countries with low energy and labor TB productivity. The EU's trade hence contributes significantly to employment in developing countries. This study showed that dislocating industries and manufacturing stages to developing countries can also increase energy (and thus environmental) footprints resulting from differences in productivity. We estimate that, by making accessible cheap labor, trade leads to an increased energy and carbon footprint of EU consumption because (1) energy productivity increases less with rising GDP than labor productivity for TB approach and (2) it enables increased consumption.

Conclusion

International trade and global production chains carry environmental and social impacts embodied in each traded good and service. Even though labor and energy productivities tend to be higher for domestic production in high-income countries than those in emerging economies, this difference is significantly reduced for consumption, when including imported products to satisfy national demand. The analysis of socioeconomic and environmental aspects embodied in consumption can shed a light on the real level of productivity of an economy, particularly in the setting of globalization and the effects of rising imports and offshoring resulting from costs and regulations. This research introduced a consumption-based metric for productivity, in which we evaluated the loss of productivity of developed nations resulting from imports from less-developed economies and offshoring of labor-intensive production. We confirmed that the labor footprint of European imports is significantly higher than the one of exports, mainly from labor-intensive primary sectors. Nearly 30% of labor embodied in imports is low skilled, whereas the proportion of low-skilled labor embodied in the EU's exports is 3 times lower. Countries with a higher share of labor embodied in trade are also among the lowest territorial energy productivities. Labor productivity shows a direct and strong relation with GDP per capita. Besides low labor TB productivity, developing countries tend to have lower-skilled jobs and to concentrate several barriers to decent work, such as child labor, inequalities, and large rates of working poor and vulnerable employment. The adoption of a consumption-based approach to productivity permits a more equitable comparison of requirements of lifestyles and final consumption, ultimately the final purposes for the economy. By adopting a consumption perspective, we can internalize the demand for requirements originated in the upstream supply chain in countries with diverse technologies and techniques. We are particularly interested in the trade-offs that have occurred between labor and energy through the supply chain. Though we cannot determine the causality of these, it is clear that there has been a strong outflow of low-skilled labor to developing countries. Offshoring labor-intensive stages of production to countries with lower TB energy productivity can offset, or even revert, gains in efficiency and climate change mitigation actions in developed countries.

Notes

1. Ayres and Warr (2005) show that, by including exergy (or useful work) as a factor of production, economic growth in the United States is explained with high accuracy from 1900 until the mid-1970s. Useful work would include physical work by humans and animals, prime movers, and heat transfer systems. That would be valid even in the presence of gains of productivity and efficiency by technological development. After 1970, an additional factor should be added to explain economic growth, which the researchers speculate to be information technology (IT).

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information S1 provides detailed discussion on the methodology presented in the article, including a detailed description of the method and equations used and background for input-output and multiregional input-output (MRIO) analysis.

Supporting Information S2: This supporting information S2 provides detailed discussion on the results presented in the article. Specific numbers and data used for productivity, economic trade, and embodied factors of production into and from the European Union (EU), and energy intensity of labor, is given.

Appendix D

Simas, M., E. Hertwich and R. Wood. 2018a. Drivers of employment and carbon emissions in global value chains. *Unsubmitted manuscript.*

Awaiting publication and not included in NTNU Open

Appendix E

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Letter to the Editor

Correlation between production and consumption-based environmental indicators
The link to affluence and the effect on ranking environmental performance of countries

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ABSTRACT

Countries and international organizations such as the European Union and the OECD work with dashboards of sustainability indicators, which include sets of pressure indicators that reflect the performance of a country. Such indicators can be calculated for production – reflecting the volume and efficiency of a national economy, but also its specialization – and with respect to consumption, which more closely reflects impacts of lifestyles and includes the effects embodied in international trade. We determined production- and consumption-based pressure indicators for greenhouse gas emissions, material, water, land use, and solid waste using the EXIOBASE global multi-regional input-output model. We investigated the correlation among different production- and consumption-based indicators with each other, with the well-known ecological footprint, and with purchasing power parity-adjusted gross domestic product (GDP_{PPP}), all expressed per capita. Production-based indicators and GDP_{PPP} were moderately correlated, with the highest correlations between the pairs [carbon, GDP_{PPP}] and [land, water] ($\rho = 0.7$) and low or no correlation between other pairs. For the footprint indicators, however, we find a strong coupling between the carbon, water, materials and ecological footprints, both to each other and to GDP_{PPP} ($\rho = 0.8$–0.9 for all combinations). In general, the consumption-based approach shows a much stronger coupling of environmental pressures to affluence than the production-based environmental indicators. The high correlations among footprints and with affluence make it difficult to conceptualize how we will decouple environmental impact from affluence at a global level. Further research is required to investigate the impact of economic specialization, and to discover new options for decoupling environmental footprints from GDP per capita.

1. Introduction

Sustainable development policies must take into account the complexity of socio-ecological systems, particularly to avoid problem shifting across regions (Helm, 2012; Peters, 2008) or environmental issues (Hertwich et al., 2014; Jin et al., 2015; Verdade et al., 2015). To illustrate the complexity of human-environment interactions, comprehensive sets of indicators to assess the impacts of production and consumption have been developed. Indicator spectra, including the Green Growth Indicator Set (OECD, 2014), the European Commission's environmental pressure indicators framework (European Commission, 2003, 2001) and the European Union's Resource Efficiency Scoreboard (European Commission, 2016) are used to assess the environmental performance of countries. Measures such as the Environmental Performance Index (Hsu et al., 2014), the Environmental Impact Index (Bradshaw et al., 2010) and the Ecological Footprint (Borucke et al., 2013) aggregate environmental pressures for multiple issues occurring within a country or region.

Indicators that account for environmental impacts within a country (following the production-based accounting principle) don't necessarily show convergence across indicator sets, often due to a country's technological specialization and resources availability (European Commission, 2003), and are thus complementary to include in indicator sets. To internalize differences not only in technology efficiency but also in production specialization, and to capture differences in resource use due to shift of industries to resource-abundant countries, some have argued that consumption-based indicators are required to capture the real sustainability of lifestyles (Peters, 2008; Peters and Hertwich, 2008; Tukker et al., 2016; Wiedmann, 2009; Wiedmann and Barrett, 2013). Consumption-based indicators, also called footprints, link the consumption of products and services with environmental impacts by accounting for pressures occurring along the global supply chains of these products. These footprints are now widely used to measure the appropriation of natural capital and resources or the generation of emissions associated with human activities.

To comprehensively capture the different aspects of sustainable lifestyles, some authors combine different footprints into a dashboard of pressure indicators, such as the footprint family (Galli et al., 2013, 2012) comprising of carbon, water, and ecological footprints; and the multi-indicator analysis to study Europe's footprints and resource deficit for carbon, land, water (in particular blue water consumption) and material (Tukker et al., 2016). Other dash-

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boards combine production- and consumption-based indicators to assess environmental impacts, such as the one used by the European Commission in its "Roadmap to a Resource Efficient Europe" (European Commission, 2011). Since the proposed dashboards of footprints were defined *a priori*, one needs to examine their actual usefulness. Do the footprint dashboards really convey a different narrative compared to single indicators? This study tries to establish the correlation between different environmental footprints with one another and with economic affluence, at the same time that it compares the national footprints with a similar dashboard of production-based pressures. We include policy-relevant indicators that have been frequent in the analysis of countries' environmental performance: ecological, carbon, water, material, land and waste.

A high correlation between environmental performance indicators of societies has two immediate consequences. First, high correlation suggests that the different environmental footprints are strongly coupled to some underlying mechanisms in the countries' socioeconomic metabolism. Decoupling one indicator from affluence or wellbeing may depend on the simultaneous decoupling of others, which means that sustainable development may represent a much larger challenge that anticipated. Second, the information content of the dashboard might be lower than the variety of indicators suggests. This may have consequences for the usefulness of such dashboards. Previous studies have shown that various environmental footprints are, at least partially, correlated with affluence (Hertwich and Peters, 2009; Wang et al., 2016; Weinzettel et al., 2013; Wiedmann et al., 2013). Other studies have shown that about half of the environmental impact indicators in the life cycle assessment of products are highly correlated to fossil energy demand (Huijbregts et al., 2010, 2006) and that product footprints for different environmental accounts are often highly correlated among each other (Pascual-González et al., 2015). These different studies suggest a potential correlation among environmental pressure caused by the production or consumption of goods and their relationship to affluence, commonly measured by GDP or consumption levels, but the degree of correlation across the board of indicators is not available in the current literature. This study tries to fill this gap.

2. Methods

We calculated the correlation of the most commonly used production- and consumption-based pressure indicators – carbon, blue water, material, land, solid waste – with one another, with the well-known ecological footprint (Borucke et al., 2013) and with affluence, measured in purchasing power parity-adjusted gross domestic product (GDP_{PPP}) per capita. We illustrated the consequences of such correlation on the ranking of countries according to their environmental pressure per capita. In addition, we investigated how an aggregated indicator based on several footprints would perform depending on how the different footprints are combined.

2.1. Calculation of environmental pressure indicators

The environmental indicators used in this analysis are listed in Table 1. The calculation of environmental footprints and production-based pressures (with exception of ecological footprint) were performed using the high-resolution environmentally-extended multi-regional input-output (EE-MRIO) EXIOBASE database (Wood et al., 2015). This input-output model details the flows of goods and services throughout the global economy, and is coupled with a variety of resource use and environmental pressures in the same classification. In its version 2.3, used in this study, EXIOBASE describes the world economic system for the year 2007 in a detailed product resolution. It comprises 43 countries, which together account for around 90% of global GDP, and five "rest-of-the-world" regions. The countries are the 27 European Union[1] countries and 15 other major world economies including the US, China, India, Russia, and Brazil. The full lists of regions in EXIOBASE are available in the supplementary information (SI). For this study we used 42 countries.[2]

Production-based pressures were calculated by summing all impacts and resource use within domestic industries and direct impacts in final demand (households, governments, and fixed capital formation). The calculation of environmental footprints was done by allocating impacts and resource use occurring domestically and in foreign regions throughout the global supply chain to the final consumption of the goods and services in the assessed country, summed with direct impacts in final demand, through an EE-MRIO analysis (Peters and Hertwich, 2004). A more detailed description of the EE-MRIO method and the data sources for environmental extensions from EXIOBASE are available in section S1 of the SI.

Production-based impacts were considered for every indicator, except for the ecological footprint, in order to maintain methodology consistency as production accounts for ecological footprints are not available from the Global Footprint Network. Population and GDP_{PPP} data for the year 2007 were retrieved from The World Bank (2016).

2.2. Correlation and construction of an aggregated indicator

We calculated Pearson product-moment correlation coefficients (ρ) for each production- and consumption-based indicator with each other and with per capita GDP_{PPP}. To illustrate the implication of these correlations, we compared the ranking of countries for each of the indicators and we aggregated the different environmental footprints into a single score. We present the aggregation of the three highest correlated footprints – carbon (C), material (M), and water (W) – into an aggregated index (I). To explore the effect of weighting on the potential compound index we performed a Monte Carlo analysis by screening 10 000 different arbitrary random weighting schemes applied to the normalized carbon, material and water footprints according to Eq. (1).

$$I(C,M,W)=\alpha\left[\frac{C-C_{\min}}{C_{\max}-C_{\min}}\right]+\beta\left[\frac{M-M_{\min}}{M_{\max}-M_{\min}}\right]+\gamma\left[\frac{W-W_{\min}}{W_{\max}-W_{\min}}\right], \quad \alpha+\beta+\gamma=100 \qquad (1)$$

3. Results and discussion

The 42 countries assessed represented the majority of impacts worldwide in 2007. For production-based impacts, these countries were responsible for 81% of global GHG emissions, 75% of domestic extraction used, 67% of blue water consumption, and 59% of global land use. When accounting for global supply chains, the share of these countries footprints in the global resource use becomes even higher: 87% for carbon, 86% for material, 80% for water, and 80% for land footprints.

Fig. 1 shows the correlation between environmental pressures indicators with one another and with GDP_{PPP} in the 42 countries assessed. On the left, it shows the correlation between production-based indicators, and on the right, the consumption-based footprints. With the notable exception of greenhouse gas

[1] EXIOBASE is currently being updated to a new version (Stadler et al., Submitted), with the inclusion of Croatia in the EU. In all versions of EXIOBASE the United Kingdom is included as an EU member.

[2] We excluded Taiwan from the analysis due to the lack of ecological footprint accounts and all rest-of-the-world regions due to the high regional aggregation.

Table 1
Environmental indicators used in this study and its coverage, units, and source of data.

Indicator	Coverage	Unit (per capita)	Source
Carbon	Greenhouse gas emissions Comprises CO_2, CH_4, N_2O, and SF_6	t CO_2e	EXIOBASE
Material	Material input to the economy Comprises primary crops, crop residues, fodder crops, grazing, wood, aquatic animals, metal ores, non-metallic minerals, and fossil fuels	tons	EXIOBASE
Water	Blue water consumption Comprises water consumed in agriculture, livestock, manufacturing, electricity, and households	m^3	EXIOBASE
Land	Total land use Comprises arable land, pastures, and forests	1000 m^2	EXIOBASE
Waste	Solid waste and scrap Solid waste comprises wood, ash, food, paper, plastic, inert or metal waste, textiles, and oil and hazardous substances for landfilling, bio-gasification, or incineration. Scrap comprises scrap metal, as well as other materials for recycling, such as construction materials, ash, glass, paper, wood, and plastics	tons	EXIOBASE
Ecological[a]	Demand on bioproductive area Comprises cropland, grazing land, fishing grounds, forest area for wood products, built-up land, and forest area to absorb CO_2 emissions	Global hectares (gha)	Borucke et al. (2013)

[a] No production-based pressure was considered for the ecological footprint.

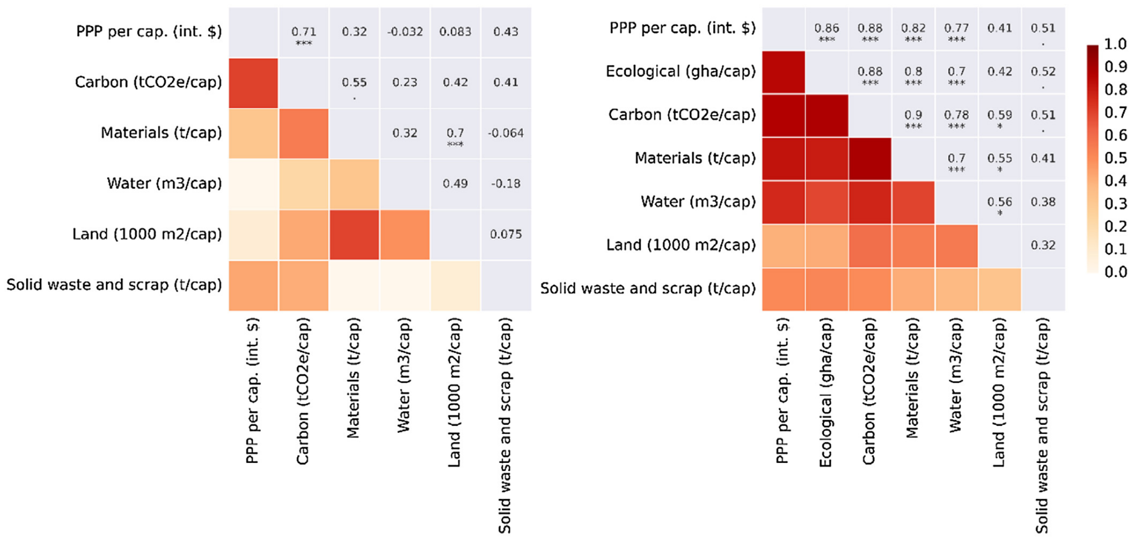

Fig. 1. Correlations (Pearson product-moment correlation coefficient) among production-based environmental pressures per capita (left) and environmental footprints per capita (right) across the 42 EXIOBASE countries and the gross domestic product per capita in purchasing power parity (GDP_{PPP} per capita) in 2007. The correlation coefficients are shown both as numbers and on a color scale. Darker shades represent stronger linear correlation. Correlation coefficients may vary between −1 and 1, where 1(−1) indicates perfect linear (anti-linear) correlation between two variables, and 0 indicates no linear correlation at all. Significant correlations are indicated by * ($P \leq 0.05$), ** ($P \leq 0.01$) and *** ($P \leq 0.001$).

emissions, pressures within country borders caused by domestic production processes are mostly not or only weakly correlated with GDP_{PPP} (Fig. 1 left). Domestic material consumption is correlated with land use and more weakly with GHG emissions, while other correlations are not significant. The lack of stronger correlations on production-based environmental pressures occurs possibly due to specific national characteristics, such as differences in natural conditions and resource endowments, economic specialization, subsidies and national industrial policies, or due to countries having taken different decisions about avoiding or mitigating such pressures (Duchin and López-Morales, 2012; Fracasso et al., 2016). Thus, different environmental accounts should be considered simultaneously to obtain a complete picture of environmental pressures occurring within the territory of a country.

Consumption-based accounts, meanwhile, show much stronger correlation to each other and to GDP_{PPP} (Fig. 1 right). Especially ecological, carbon, materials, and water footprints show high correlation among themselves and to GDP_{PPP}. The correlation of waste footprint with other indicators is weak and so is the correlation of the land footprint with the ecological footprint and the GDP_{PPP}. The correlation between production- with consumption-based indicators can be found in Fig. S1, in the SI.

Comparing the two panels in Fig. 1, we find that considering the effect of trade either introduces or significantly strengthens the correlations among the different pressure indicators. Such an increased correlation is in itself not surprising, as we subtract things that are unique for countries and add from a common pool. We would argue, however, that the strength of the effect is still noticeable. A growing body of literature has studied the role of

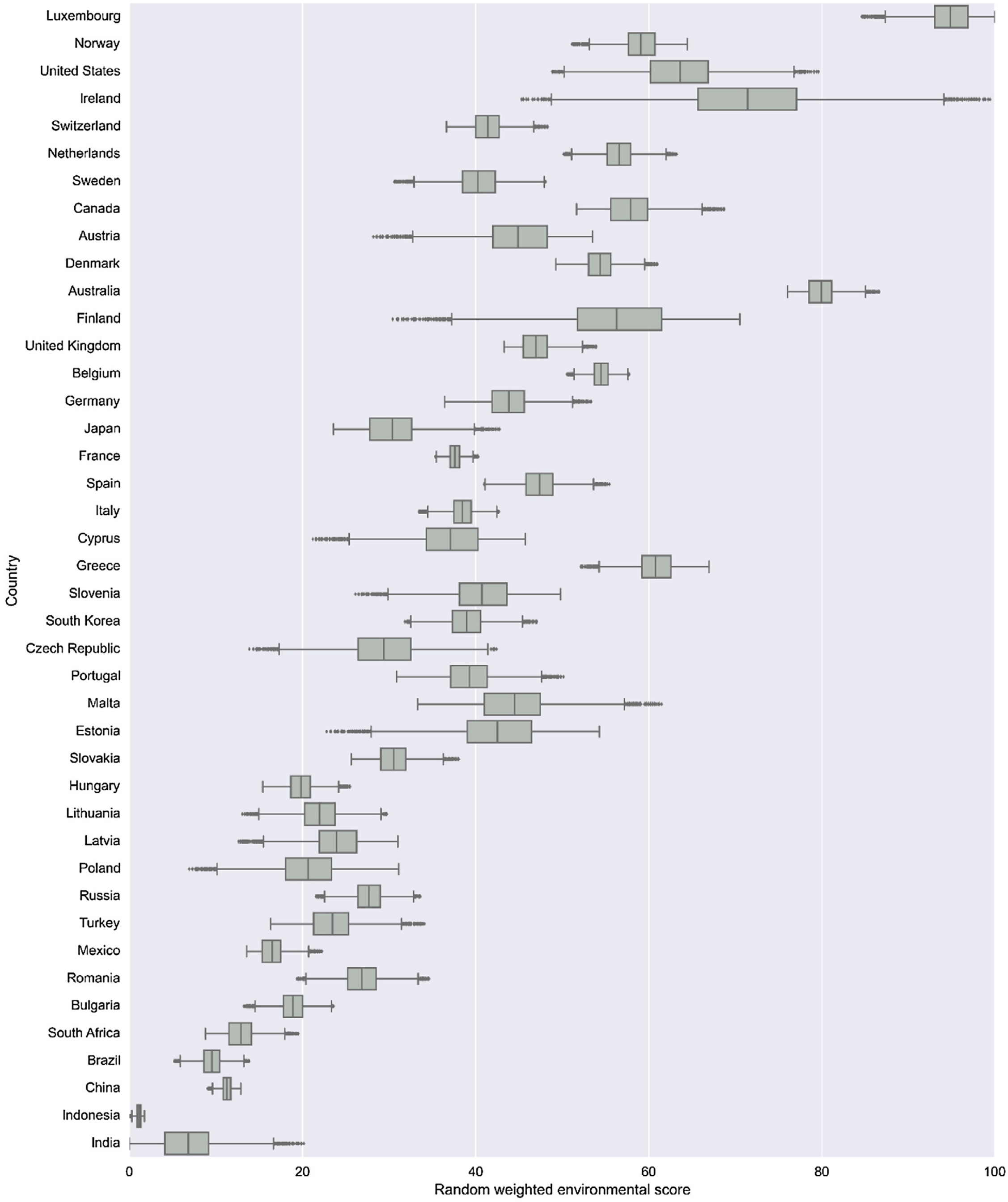

Fig. 2. Environmental scores obtained from arbitrary random weighting of the carbon, water and material footprints for the 42 EXIOBASE countries, 10 000 simulation runs. Countries ordered by GDP_{PPP} per capita. The middle line of each box shows the median, the box spans the inter-quartile range (25–75% of data points) with the whiskers spanning 1.5 time this inter-quartile range. Points outside this range are indicated by discrete points.

industry outsourcing in the reduction of production-based environmental impacts and the growth of "virtual" flows of impacts through trade (Dittrich et al., 2012; Hertwich et al., 2010; Peters and Hertwich, 2008; Tukker et al., 2016, 2014; Wiedmann et al., 2013). Other factors may be needed to explain this pattern. The increasing specialization of countries in their production may contribute to differences in environmental pressures, while increasingly similar lifestyles comprising the consumption of some of the same consumer products may contribute to the high correlation of footprint indicators. If similar products with similar footprint intensities are consumed, higher expenditure will drive higher impacts.

Previous studies have found high correlations between the carbon (Hertwich and Peters, 2009), land (Weinzettel et al., 2013), and material (Schandl et al., 2016; Wiedmann et al., 2013) footprints with GDP. A high correlation of materials and water footprints was also expected, as an important part of materials footprints is related to biomass, and between materials and carbon footprints, as carbon-intensive construction materials such as steel, cement and fossil fuels constitute most of the growth in material footprints in the past decades (Allwood et al., 2010; Dittrich et al., 2012). A significant correlation of ecological footprint with the land and carbon footprints was expected, as the ecological footprint contains components of land use and land theoretically required to absorb emitted carbon (Borucke et al., 2013; Giampietro and Saltelli, 2014). We find a significant correlation with carbon but not land footprints. In addition, we find a low correlation between the land footprint and GDP_{PPP}. These low correlations may be due to differences in the calculation of the land footprint. For the ecological footprint, Borucke et al. (2013) normalized land use with crop- and country-specific yield factors to obtain a global equivalent land use that is a reflection of the biomass production potential consumed rather than the actual land use. Weinzettel et al. (2013) also used this equivalent land use and in addition controlled for the per-capita availability of fertile land. In this study, however, we use total land use, without distinction of productivity or land availability. The solid waste and scrap footprint, which measures the total solid waste and scrap generated in a country's global supply chain, is only weakly correlated with the GDP_{PPP}-carbon-materials cluster, which may be a result of very different waste intensities across industrial sectors and countries, but large data gaps remain for this account (Merciai et al., 2013).

One application of per-capita environmental pressure indicators and footprints has been for producing country rankings, which are supposed to reflect the performance of a country in comparison with others. We explore the effect of the observed correlations on the rankings, by (1) comparing rankings produced with different indicators in Table 2, and by (2) evaluating an arbitrary weighting of a carbon-water-material footprints index in Fig. 2.

Country rankings based on different production-based environmental pressure indicators are not very consistent across the different environmental issues investigated (Table 2 left). The ranking pattern changes, however, when switching to consumption-based accounting (Table 2 right). The country rankings based on different footprints per capita are more similar, reflecting the correlation among underlying footprints. Internalizing trade in the country rankings show that, although technology changes are vital for a country's production-based impacts, higher consumption per capita of goods produced elsewhere have a substantial impact on decreasing the environmental performance of affluent countries. As reflected by the high correlations between footprints and GDP_{PPP}, similar trends of increasing environmental pressures with personal purchasing power can be observed across mainly carbon, material, and water accounts compared to the production-based rankings.

There are a number of outliers, however, that should be addressed individually. For example, the high land and waste footprints for Russia, which scores low on the other indices, and the high water footprints of Malta and Greece. Curiously, two countries with a very high per capita GDP_{PPP} present relatively low footprints for material (Switzerland) and ecological (Norway). These outliers might be influenced either by different consumption patterns, unique technologies or policies in local production, and to some extent data quality and availability. These cases show that, while there is much more consistency in the environmental performance of countries when looking through a consumption-based approach, there might be important differences in the resource appropriation of different countries. A thorough study of these differences and how they have changed in recent years might contribute to understanding how to improve decoupling of environmental footprints from GDP per capita.

The environmental production-based pressures and footprints per capita for each country are available in Table S2 the supplementary information. One could cluster countries with similar characteristics and perceive the similarities in their environmental pressures. For example, countries with highest land area and highest availability for fertile land per capita (Australia, Canada, Russia) have high pressure on land when accounted for both production-based pressures and footprints. Countries with the lowest land availability per capita (Malta, South Korea, Switzerland, Netherlands, Belgium) have high ratios between land footprints and production-based pressures, showing their dependency on imported embodied land. Higher differences between production-based pressures and footprints are seem for land and water accounts.

The high correlation between the carbon, material and water footprints raises the question whether the information contained in these indicators could be conveyed in one single aggregate measure. Deriving an index based on the aggregation of multiple indices includes a normative aspect: how much weight should be given to each individual indicators before the aggregation. However, since the indicators considered here are highly correlated (material, carbon and water footprint, see Fig. 1), different weighting schemes should only have a limited effect on the country ranking and reveal the same trend of higher environmental stressor with increasing affluence as observed for the individual indicators. To test this hypothesis, we performed a Monte Carlo analysis with 10 000 randomly chosen weighting schemes.

This leads to compound indices that cover rather narrow ranges for many countries, including the Netherlands, France, or Brazil (Fig. 2), but a much higher spread for other countries, including Ireland, Finland, and India. The latter three countries are characterized by one single deviating footprint which lie outside the range expected based on the other indicators for this country. Ireland, for example, has a particular high material footprint (see Tables 2 and S2); the weighting scheme focusing on the material requirements lead to amplify the scores, which put Ireland at the top of all countries. Finland, on the other hand, has a particular low water footprint. Therefore, the weighting schemes which put a focus on the water footprint result in a low overall score for Finland. For India, the water footprint is much higher than it would be expected based on affluence or the other footprint values. Nevertheless, the overall trend of increasing footprints with increasing level of affluence appears to be robust and, in most cases, insensitive to the applied weighting schemes. For footprints with lower correlations, the ranges increase considerably. For all production-based pressures, no trend can be identified (see also Figs. S2 and S3).

4. Conclusion

Due to different socioeconomic and technological characteristics, production-based environmental impacts vary significantly across countries. Each of the indicators for the various environmental pressures indeed provides distinct information. In contrast to production, consumption-based footprints offer more uniform patterns of environmental impact on the national level. The relative performance of a country with respect to one environmental footprint provides a good indication as to how this country will per-

Table 2
Ranking of the 42 EXIOBASE countries according to their footprints and production-based accounts for different indicators. Countries are ordered by GDP_{PPP} per capita, from highest to lowest. Rankings vary from 1 (red, higher values per capita) to 42 (green, lower values per capita). (For interpretation of the references to colour in this table legend, the reader is referred to the web version of this article.)

Country	Production: Waste	Production: Land	Production: Water	Production: Material	Production: Carbon	Footprint: Waste	Footprint: Land	Footprint: Water	Footprint: Material	Footprint: Ecological	Footprint: Carbon	PPP per capita
Luxembourg	2	31	39	39	1	2	3	1	2	1	1	1
Norway	20	9	24	2	7	9	5	10	5	15	8	2
United States	27	10	2	10	3	25	12	5	13	3	3	3
Ireland	38	14	31	3	8	21	8	13	1	8	4	4
Switzerland	11	33	35	34	29	14	16	17	20	14	17	5
Netherlands	3	41	30	31	16	4	7	4	12	7	11	6
Sweden	6	6	23	8	30	11	13	21	14	6	23	7
Canada	19	2	13	5	4	20	2	9	9	5	5	8
Austria	7	19	26	12	19	7	24	23	6	16	15	9
Denmark	23	28	9	9	9	12	15	12	7	2	9	10
Australia	25	1	1	1	2	22	1	2	3	10	2	11
Finland	4	4	20	4	11	3	6	22	4	9	6	12
United Kingdom	9	35	33	35	20	5	22	14	18	21	13	13
Belgium	5	39	22	27	14	8	10	8	10	4	10	14
Germany	10	34	28	24	13	6	21	18	19	23	14	15
Japan	8	37	41	40	18	10	29	28	31	27	20	16
France	16	24	14	26	31	15	9	15	23	20	27	17
Spain	17	16	4	18	26	23	20	7	17	19	24	18
Italy	21	32	12	32	24	18	25	16	25	22	22	19
Cyprus	32	36	40	7	15	29	35	31	16	26	19	20
Greece	30	21	3	17	5	17	11	3	8	18	7	21
Slovenia	13	17	36	11	22	13	19	26	15	17	16	22
South Korea	29	40	38	36	17	32	27	20	21	24	18	23
Czech Republic	22	26	27	13	12	26	34	34	27	13	21	24
Portugal	26	23	8	15	33	28	23	11	22	28	30	25
Malta	33	42	10	42	25	33	30	6	26	31	25	26
Estonia	18	8	42	6	6	16	14	29	11	11	12	27
Slovakia	15	22	21	29	23	24	31	27	29	32	26	28
Hungary	35	20	15	30	32	34	38	33	35	34	33	29
Lithuania	24	12	34	28	36	19	32	36	32	25	31	30
Latvia	40	7	37	22	38	30	18	37	28	12	32	31
Poland	14	27	32	20	21	27	37	41	30	30	29	32
Russia	1	3	16	16	10	1	4	24	33	29	28	33
Turkey	34	25	5	33	37	37	33	19	36	38	35	34
Mexico	39	13	17	37	39	39	28	30	38	35	38	35
Romania	36	18	6	14	35	38	36	25	24	39	37	36
Bulgaria	31	15	11	19	28	36	39	35	34	33	34	37
South Africa	28	11	25	23	27	35	26	40	40	37	36	38
Brazil	37	5	18	21	40	40	17	38	37	36	40	39
China	12	30	19	25	34	31	40	39	39	40	39	40
Indonesia	42	29	29	38	41	41	41	42	41	41	41	41
India	41	38	7	41	42	42	42	32	42	42	42	42

form on some other environmental footprints, especially carbon, material, ecological, and water footprints.

It is natural that countries specialize in production due to their own endowments, whereby the domestic pressure reflects the role of a country in a global supply chain. In contrast, footprints reflect the purchase of individuals within a country, which partially concentrate on the same commodities due to globalized consumption patterns and due to similar needs. Consequently, the resource requirements for inhabitants of countries with comparable development status do not vary substantially.

In addition, domestic technology greatly influences production-based accounts. Countries with high resource intensity of domestic production export commodities with a relatively high footprint. Taking into account global supply chains and trade tends to balance countries' production specialization and technologies, leading to an alignment of most footprint measures with GDP per capita, even if the countries' respective production-based accounts diverge. Indeed, a structural analysis of carbon embodied in trade indicates that specialization and resource intensity are about equally important in explaining carbon trade balances (Jakob and Marschinski, 2013). The result is a much more consistent ranking of countries based on their footprints per capita than on their production-based pressures per capita.

The low variance between footprint-based environmental performance indicators suggests that decoupling environmental impacts from lifestyles might be more difficult than decoupling within national boundaries. Several major environmental footprints are highly correlated with GDP. We thus need further policy options that drives a wedge not between production-based indicators and economic output, but consumption-based indicators and GDP.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2017.01.026.

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Appendix F

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Appendix G

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Article

The "Bad Labor" Footprint: Quantifying the Social Impacts of Globalization

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Abstract: The extent to what bad labor conditions across the globe are associated with international trade is unknown. Here, we quantify the bad labor conditions associated with consumption in seven world regions, the "bad labor" footprint. In particular, we analyze how much occupational health damage, vulnerable employment, gender inequality, share of unskilled workers, child labor, and forced labor is associated with the production of internationally traded goods. Our results show that (i) as expected, there is a net flow of bad labor conditions from developing to developed regions; (ii) the production of exported goods in lower income regions contributes to more than half of the bad labor footprints caused by the wealthy lifestyles of affluent regions; (iii) exports from Asia constitute the largest global trade flow measured in the amount bad labor, while exports from Africa carry the largest burden of bad labor conditions per unit value traded and per unit of total labor required; and (IV) the trade of food products stands out in both volume and intensity of bad labor conditions.

Keywords: social footprint; international trade; social impacts of consumption; labor conditions; supply chain; consumption-based accounting; multiregional input-output model

1. Introduction

Bad labor conditions exist around the world, but just how much of this bad labor is driven by the globalization of production chains? The rapid increase in the volume of international trade and the spread of manufacturing stages across the globe has dispersed environmental, social, and economic impacts. It is becoming increasingly harder to trace the origins of consumed products. Attention is often drawn to bad labor conditions when high-profile incidents events occur, as in the case of the death of over one thousand workers caused by the Bangladeshi Rana Plaza garment factory collapse in April 2013, in hundreds of deaths and human rights violations during construction works related to the 2022 FIFA World Cup in Qatar [1–3], or in recent slavery conditions uncovered at sugarcane plantations in Brazil [4]. Consumers and retailers alike have expressed the desire for humane working conditions in the supply chains of products [5–8]. Companies have been gradually adopting proactive measures, with examples such as the Fairphone initiative [9] and the recent announcement by Intel on the use of conflict-free minerals [10]. Recently, regulations aim to promote supply chain sustainability, such as the California Transparency in Supply Chains Act of 2010 and the (unsuccessful) Transparency in UK Company Supply Chains (Eradication of Slavery) Bill 2012–2013. Media reports and NGO campaigns suggest that consumers, retailers and brand-owners in Europe and North America are not unaffected by-standers but beneficiaries of bad labor conditions, indicating a moral responsibility to counter them [11]. Many case studies demonstrate that bad labor conditions, such as child labor, forced labor, and poor working conditions and pay, are associated with the production of internationally traded goods [12–17]. However, just how important are the global supply chains of traded products to the problem of poor labor conditions? Which consumers and which product groups are most relevant in tracking the "embodied" poor labor conditions from source to destination? In this paper, we quantify the extent to which bad labor conditions are related to internationally traded products using a new model of global production and consumption.

Institutions such as the International Labor Organization (ILO), The United Nations Statistics Division (UNStats), the World Bank, and the OECD Statistics Division (OECD Stats) provide useful statistics and indicators to assess social and labor conditions around the globe. Available labor statistics show the global distribution of work conditions from the point of view of where it occurs, both regionally and in which economic sectors [18–20]. Until now, however, it has not been quantified how much of these undesirable "bad" labor conditions is associated with the globalization of production chains.

Many studies conclude that trade openness and foreign investments increase income, reduce inequalities, and thus have positive effects in labor conditions in domestic production, such as the reduction of child labor [21–26]. At the same time, however, the globalization of production chains and the growing cross-country inequalities [27] demand a combination of local, regional and global policies to eradicate extreme poverty and inequality and to provide good work conditions and access to the market for everyone [28,29]. Policies focusing on banning or boycotting goods produced with bad labor practices can have the opposite effect as desired, as it increases the wage gap between good and poor work practices, as it generates less income to poor households. The increased wage gap penalizes poor households by leading not to the reduction, but maintenance or even increase of poor work to achieve subsistence levels [21,23], and reduces the market prices of goods produced with bad labor relative to certified products made in good labor conditions [30]. At the same time, economic growth is not enough to reduce bad labor conditions [31]. Local and regional policies aiming to reduce wage distortions, increase human capital, and provide universal access to education lead to long-run economic development and decrease in bad labor conditions [21]. Child labor, for example, derives mostly from poor households whose short-term benefits from income generated by the children exceed the benefits of sending the children to be educated. For the poorest households, increases in income generated by local and regional economic development may push the household above its subsistence threshold, allowing it to reduce or eliminate its dependence on child labor income [22].

Traditional trade theory, based on factor endowments, suggests that countries with high labor availability specialize in the production and exports of labor-intensive goods [32,33]. The spread of production stages among several countries and regions implies, however, that countries do not necessarily specialize in production of determined goods, but mostly in particular stages of the production process for which the country has the lowest opportunity cost [34,35]. This would suggest that labor-intensive stages of production, especially those that demand less skilled and less specialized labor, would progressively migrate from regions with higher labor costs to labor-abundant regions. Recently published labor footprints show that the majority of physical labor required to produce traded goods, either in the direct production or in the upstream supply chain of those goods, follows a clear path from developing to developed countries while wages flow between developed nations [36]. Less developed economies are net exporters of labor embodied in products and high-income countries are net importers [37]. With high flows of low-paid labor from developing countries associated with the production of goods supplied to affluent nations, the investigation of labor conditions associated with those products becomes critical.

Recent efforts have mapped bad labor conditions associated with production in different regions. Examples of these efforts include the Social Hotspots Database [5], the List of Goods Produced with Child Labor or Forced Labor [38], the Global Slavery Index [39], and the Slavery Footprint [40]. Although previous studies provided valuable insights to some bad labor indicators associated with different products and specific manufacturing stages, identifying impacts related to all stages of production spread in different industries and regions is only possible by using a global multi-regional input-output (MRIO) analysis. MRIO is a comprehensive method for calculating footprints based on the consumption of final products. It traces all correlations between industries in different sectors and regions, and estimates total output from intermediate industries contributing to the upstream supply chain for each product consumed [41].

Consumption-based studies through MRIOs are being increasingly used for analyzing the displacement of environmental pressures and resource requirements. The task of integrating social indicators to that analysis is still a challenge, mostly due to the availability and level of regional and sectorial aggregation of social indicators. Here, we attempted to move one step closer to overcome those obstacles in this study by quantifying on a global scale the bad labor associated to production and the paths and flows of goods and services from the place of origin to the final consumer. We expect that growing international trade, multinationals presence, and offshoring and outsourcing in search for lower production costs mean that the distance between social externalities in production in poor regions to support prosperous lifestyles get smaller.

We quantified six bad labor conditions: occupational health damage, vulnerable employment, gender inequality, predominance of unskilled and low-skilled labor in workforce, child labor, and forced labor. We aimed to quantify: (i) the contribution of inter-continental trade to bad labor footprints in the seven world regions assessed; (ii) the sectorial contributions to bad labor footprints; and (iii) the bad labor intensities of imports, exports, and domestic production for each of the regions.

2. Methods

This section presents the methods used in the study. First, it defines the bad labor indicators used and describes the model. More detailed method and data structure descriptions and sources are available in the online Supplementary Material (S1).

We calculated indicators for undesirable work conditions associated with consumption, the *Bad Labor Footprint*, as presented and detailed in Table 1. We used a consumption-based approach to calculate footprints and a fully-integrated MRIO model. Different measures of bad labor intensities were compared to provide relative impact of consumed products. We do not prioritize or weight the bad labor measures; we present independent results for the different footprints.

2.1. Bad Labor Measures

This section presents a brief description of each of the bad labor measures and associated indicators assessed in this study. A detailed description of how each of them was calculated and allocated in the model can be found in the online Supplementary Material (S1).

2.1.1. Occupational Health Damage

Estimates place over 300,000 worker deaths and 3.5 years of healthy life lost globally for every 1000 workers as a result of occupational injuries every year [42]. These estimates do not include disabilities resulting injuries. If diseases resulting from occupational exposure to asthmagens, carcinogens, noise, and ergonomic stressors are also taken into account, death counts can reach up to 850,000 and healthy life lost can rise to over 8 years per 1000 workers [43]. The indicator used to evaluate occupational health damage is disability-adjusted life years (DALY), which measures the gap between the current situation and an ideal one in which everyone lives to the standard life expectancy in perfect health [44,45]. It comprises the time lived with disabilities and the time lost due to premature mortality.

Table 1. Summary of labor and bad labor indicators used in the study.

Measure	Indicators	Unit	Definition	Spatial Detail of Original Data	Temporal Detail	Source
Total labor	Total labor	Persons-year equivalent ($p\text{-}y_{eq}$)	Total employment required for the production of goods and services	EXIOBASE [(1)]	2007	[19,46]
Occupational health damage	Incidence of burden of disease for cancer of the trachea, bronchus and lung; leukemia; chronic obstructive pulmonary disease; asthma; noise-induced hearing loss; low back pain; and injuries	Disability-Adjusted Life Years (DALY)	Measures the gap between the current situation and an ideal situation in which everyone lives up to the standard life expectancy in perfect health. It combines the time lived with disabilities and the time lost due to premature mortality	Africa, Middle East, North America OECD, Latin America and the Caribbean, Europe OECD, Europe Other, Asia and the Pacific	2000	[43,47,48]
Vulnerable employment	Persons in total labor without employee status	Persons-year equivalent ($p\text{-}y_{eq}$); Share of total labor (%)	Workers without proper coverage of labor regulations and guarantees. It comprises unpaid contributing family workers and own-account workers.	EXIOBASE [(1)]	2007	[19,46]
Gender inequality	Women in workforce, as a share of total labor	Share of total labor (%)	Share of women in the labor market	EXIOBASE [(1)]	2007	[19]
Incidence of unskilled and low-skilled workers	Low-skilled labor, in absolute values and as a share of total labor	Persons-year equivalent ($p\text{-}y_{eq}$); Share of total labor (%)	Employment in elementary occupations [49] and/or employees with educational attainment levels until (and including) primary education [50]	EXIOBASE [(1)]	2007	[19]
Child labor	Children in child labor and in hazardous child labor	Persons-year equivalent ($p\text{-}y_{eq}$)	Work done by children who are younger than the designated minimum working age and children in hazardous labor, that is, in worst forms of labor due to moral, health, and safety risks. Can include children in forced labor.	Asia and the Pacific, Latin America and the Caribbean, Sub-Saharan Africa, Other regions	2004 to 2008	[18]
Forced labor	Workers in forced labor	Persons-year equivalent ($p\text{-}y_{eq}$)	All work or service which is not performed voluntarily, including debt bondage. Can include children in forced labor.	Asia and the Pacific, Latin America and the Caribbean, Africa, Middle East, Central and South-Eastern Europe (non-EU) and CIS, Developed economies and the EU	2002 to 2011	[51]

[(1)] 43 countries, consisting of all countries in the Europe Union (EU-27) plus 16 countries (Norway, Switzerland, United States, Canada, Australia, Japan, South Korea, Taiwan, Turkey, Russia, Mexico, Brazil, South Africa, China, Indonesia, and India); plus five Rest of the World (RoW) regions (Africa, Middle East, Asia and the Pacific, Latin America and the Caribbean, and Other Europe).

2.1.2. Vulnerable Employment

Persons in vulnerable working conditions are those with large economic risks associated with their jobs. They are less likely to have formal employment arrangements, and are more susceptible to economic cycles and environmental disasters. Workers considered to be in vulnerable conditions are those classified as own-account workers and contributing family workers, that is, with no formal employment bonds [52]. Vulnerable employment affects approximately half of the total employment pool. In developed economies, vulnerable employment accounts for around 10% of total workers, while in regions like South Asia and Sub-Saharan Africa they comprise nearly three quarters of total workforce [20]. Vulnerable employment can indicate a number of other work-related conditions, such as: informal employment, workers not covered by social security and by formal labor regulation and representation, workers without contribution to and benefits from pension schemes, workers with no possibility of paid leave due to sickness or invalidity, workers without or with limited rights to parental leave, and workers with no stability and security of work.

2.1.3. Gender Inequality

Women empowerment and access to education and the labor market is still a goal for several developing regions. Globally, only 48% of working age women were employed in 2007, in contrast to 73% of men. In some regions, however, this difference is even higher, as in the case of South Asia (33% of women and 79% of men), North Africa (19% of women and 67% of men) and the Middle East (15% of women and 67% of men) [20]. We measure gender inequality by quantifying the share of women in the workforce relative to total employment.

2.1.4. Incidence of Unskilled and Low-Skilled Workers

Unskilled and low-skilled workers (henceforth called low-skilled workers) are those who perform elementary occupations [49] and those who have a level of education attainment up to lower secondary education [50]. A high share of low-skilled workers implies low diversity of the economy and lower economic productivity, as well as lower human capital and lower value added in production. It often indicates sub-optimal use of human resources. Although employment in low-skilled labor is not necessarily a bad labor condition in of itself, the predominance of low-skilled workers in the production of exported goods can indicate other aspects of poor working conditions, such as working poverty, low wages, income inequality, limited education attainment of adult population, and widespread poverty. The indicators used to measure the prevalence of low-skilled workers are number of low-skilled workers and the share of these in total labor force.

2.1.5. Child Labor

Child labor refers to work performed by children who are younger than the designated minimum working age, which is usually 13 to 15 years old, and all children under 18 who are involved in the worst forms of child labor, namely modern-day slavery, sexual exploitation, illicit activities, and hazardous work. Over 215 million children were estimated victims of child labor worldwide in 2008, most of which worked in agriculture [18]. Only one in every five working children is in paid employment, and the overwhelming majority (around two thirds) are unpaid family workers. Over half of the children involved in child labor perform hazardous activities, that is, activities that may affect the child's safety, health, and moral development. Such activities include work with heavy equipment, work that involves exposure to toxic substances, and work that does not allow the possibility of returning home each day. Although all forms of child labor are undesired, children in hazardous work are treated as a proxy for children in the worst labor conditions. Hazardous child labor can include children in forced labor. We quantify both children in child labor and children in hazardous child labor.

2.1.6. Forced Labor

The ILO [51] estimates that 20.9 million people are victims of forced labor globally. Force labor includes all form of work made by coercion, debt bondage, or withholding of documentation or pay, and all human trafficking for both labor and sexual exploitation. Forced labor in economic activities, associated to supply chains for manufactured products consumed worldwide, cover around 68% of total modern-day slavery, or about 14.2 million workers. Most forced labor is concentrated in non-technological, traditional work that feeds in local economies, especially in agriculture, brick-making, mining and quarrying, textile manufacture, domestic service, forest clearing, and charcoal-making [53]. Not all of forced labor is performed by adults; around one quarter of all forced labor is estimated to be executed by children.

2.2. Multi-Regional Input-Output Model

Input-output (IO) analysis is an economic approach, constructed from observed data from a particular year and region and which considers flows of products between economic sectors and to final consumption. Social and environmental impacts can be calculated with this framework by using a socially and environmentally extended input-output table that attributes requirements and impacts to each industry or product.

The social burdens in the global supply chains were calculated through a multi-regional input-output (MRIO) model, EXIOBASE (version 2) [54,55]. The model represents the world economy for 2007, and comprises 163 industries and 200 products traded within and between 43 countries (all countries in the Europe Union plus Norway, Switzerland, United States, Canada, Australia, Japan, South Korea, Taiwan, Turkey, Russia, Mexico, Brazil, South Africa, China, Indonesia, and India) and 5 broad "rest of the world" regions (Africa, Asia and the Pacific, Latin America and the Caribbean, Middle East, and Rest of Europe). All sectors are listed in table S1.6 in the Supplementary Material (S1). MRIOs comprise not only each region's IO table, but also traces the origin and destiny of traded products between different regions.

The MRIO model comprises three sections:

(1) the inter-industry model (Z), which shows the flows of products between industries;
(2) the final demand matrix (Y), which contains direct expenditures to both domestic and imported products from households and governments and to capital formation; and
(3) a matrix (F) comprised of factors of production associated with each economic sector. Factors of production are requirements, such as labor, and burdens, such as pollution, expressed per unit of output from each industry.

The model is represented in a simplified manner below in Equation (1), where each region is denoted by a number (1, 2, 3, …, n) and each matrix element is represented by a letter (Z, y, F). For detailed literature on input-output algebra and a description of extended input-output methods, we recommend the reading of Peters and Hertwich [56] and Miller and Blair [57]

$$\begin{pmatrix} \mathbf{Z}^{11} & \mathbf{Z}^{12} & \mathbf{Z}^{13} & \dots & \mathbf{Z}^{1n} \\ \mathbf{Z}^{21} & \mathbf{Z}^{22} & \mathbf{Z}^{23} & \dots & \mathbf{Z}^{2n} \\ \mathbf{Z}^{31} & \mathbf{Z}^{32} & \mathbf{Z}^{33} & \dots & \mathbf{Z}^{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{Z}^{n1} & \mathbf{Z}^{n2} & \mathbf{Z}^{n3} & \dots & \mathbf{Z}^{nn} \end{pmatrix} \begin{pmatrix} \mathbf{y}^{11} & \mathbf{y}^{12} & \mathbf{y}^{13} & \dots & \mathbf{y}^{1n} \\ \mathbf{y}^{21} & \mathbf{y}^{22} & \mathbf{y}^{23} & \dots & \mathbf{y}^{2n} \\ \mathbf{y}^{31} & \mathbf{y}^{32} & \mathbf{y}^{33} & \dots & \mathbf{y}^{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{y}^{n1} & \mathbf{y}^{n2} & \mathbf{y}^{n3} & \dots & \mathbf{y}^{nn} \end{pmatrix} \tag{1}$$
$$\begin{pmatrix} \mathbf{F}^{1} & \mathbf{F}^{2} & \mathbf{F}^{3} & \dots & \mathbf{F}^{n} \end{pmatrix}$$

With this model, we can trace manufacturing stages happening in different industries and regions represented in the Z matrices, and final products traded between countries in the y matrices. Production and consumption of domestic products are found on the diagonal, represented by Z^{xx} and y^{xx}, and traded goods between different regions are found in off-diagonal elements, represented by Z^{xn} and y^{xn} (from region *x* to region *n*). The F^{x} matrix characterizes the direct impacts associated to each industry, which allow us to estimate social impacts associated to each manufacturing stage in each region.

2.3. Data and Allocation

Data on bad labor indicators are specified in Table 1. Economic and trade data, as well as total labor data, are from the EXIOBASE model. Labor data are derived from national labor force and industrial surveys [19,46]. Data on occupational burden of diseases was obtained from Concha-Barrientos *et al.* [47], the European Commission [48], and Nelson *et al.* [43]. Vulnerable employment and work divided by skill level and gender originate from ILO LABORSTA database [19], and child and forced labor were obtained through ILO reports [18,51]. Population and gross domestic product (GDP) per purchasing power parity (PPP) data are retrieved from The World Bank Database [58]. The model represents a picture of international economy and labor conditions in 2007.

Although labor statistics such as the number of employees in each economic sector are usually well covered by labor force and industry surveys, the quality of these jobs is usually based on estimates, and therefore carry a great deal of uncertainty. That is mostly true for statistics on some of the worst labor conditions, such as child and forced labor. Statistics on these forms of work are scarce; their illegal nature makes it difficult to collect statistically representative data—over 90% of slavery in Europe is estimated to go undetected [59]. Additional factors include statistical survey design [60], and insufficient effort from government agencies to collect and make available these data [38].

The allocation of bad labor conditions into EXIOBASE sectorial and regional classification was performed based on employment share [37]. We assumed that, within a region, the rate of bad labor per total labor in each broad sector was similar. Broad sector, here, is considered aggregated sector classification from the original data. Furthermore, due to the lack of information, we do not distinguish between goods produced for domestic consumption and those produced for export within a sector. Even though previous studies have pointed at the existence of better conditions in exporter-oriented companies than those oriented to the domestic market (e.g., Alvarez and Lopez [61]), we do not have sufficient information to distribute the bad labor across products sold in the domestic and international market. This is a limitation of this study, and provides a basis for further research as more data become available. Child and forced labor were allocated according to the share of low-skilled labor, under the assumption that these positions are more likely to concentrate these worst forms of labor. More details on allocation can be found in Section S1.1.2 of the Supplementary Material (S1).

Original data for child and forced labor presented high sectorial and regional aggregation (three sectors economy and 4 and 6 regions respectively). Therefore, results were re-aggregated in seven regions and eight consumption categories in order to avoid a false representation of the resolution of the analysis. The aggregated regions for analysis are (1) Africa; (2) Asia and the Pacific; (3) Europe OECD; (4) Latin America and the Caribbean; (5) Middle East; (6) non-OECD Europe; and (7) North America. The aggregated consumption categories represent groups of products and services purchased by final consumers, and they are (1) food; (2) clothing; (3) shelter; (4) construction; (5) manufactured products; (6) mobility; (7) services; and (8) trade; consumption category aggregation is detailed in Table S1.6 in the Supplementary Material (S1). Each consumption category refers to a basket of products and services purchased by final consumers.

We calculated the bad labor footprints through a consumer perspective. It analyzes *what drives* the bad labor footprint, and allocates all bad labor associated to the upstream supply chain to the final consumed products. With this methodology, the bad labor footprint associated to manufactured products, for example, accounts for all bad labor conditions associated to not only the manufacture of these products, but also to the remaining industries providing intermediate goods and services to the production of those goods. In analyzing what drives the footprints, we also keep track of where the bad labor actually occurs—allowing the traceability of, for example, the labor impacts of agriculture in Asia, through processing in international supply chains to the ultimate goods purchased by consumers.

We account for the bad labor flows for trade occurring both inside a region and between different regions. Goods and services produced and consumed within a country or traded between countries within the same region (for example, from France to Italy) are considered intra-region ("domestic") trade. Alternatively, traded products between countries in different regions are included in inter-region flows ("imports" and "exports"). The footprints are calculated over a region's consumption, that is, domestic and imported products to final demand. All footprints were calculated for the full MRIO model, at sector- and region-level detail.

Footprints were calculated both in absolute DALY or persons-year equivalents (p-y_{eq}) in bad labor, and in relative values (DALY or p-y_{eq} in bad labor per 1000 p-y_{eq} in total labor footprint). Different measures of intensity were calculated based on the bad labor footprint and compared. Intensity is presented relative to four different measures: bad labor intensity of the economy (DALY or p-y_{eq} in bad labor per million euros of GDP); bad labor intensity of consumption (DALY or p-y_{eq} in bad labor per million euros expenditure); bad labor per capita (DALY or p-y_{eq} in bad labor per 1000 persons in total population); and bad labor intensity of total labor footprint, or bad labor intensity of the labor footprint (DALY or p-y_{eq} in bad labor per 1000 p-y_{eq} in total labor). Person-year equivalent represents the amount of work that would be made by a person during a year. Gross Domestic Product refers to domestic economy of the entire region, not of individual countries. It was calculated by summing the value added of the production for each country in the region, including taxes and excluding subsides.

3. Results

3.1. Consumption in Affluent Countries Drives Bad Labor Transfer

We find a clear distinction between the structure of bad labor footprints for developed and developing regions. This is mainly due to the fact that developing countries export large amounts of primary products with low value added and high labor intensity, while developed countries export goods and services with high value added and lower labor intensity [62,63]. Most of the total labor and the bad labor, in absolute numbers, occur in developing countries, and most of it is associated with the production of goods and services traded within a region. Nevertheless, the consumption of imported products originating from developing countries carry significant amount of bad labor conditions associated to their production. This is especially true for food products. The consumption of these imported products can increase the bad labor footprints of developed economies by up to 150%.

Table 2 shows footprints for each bad labor indicator in absolute values and split into the domestic and imported shares. It also displays the bad labor footprint of exports from the region, and how much products destined for export contribute to total bad labor occurring in the region. In the case of exports, the share is not based on the footprint of consumption, but to the total bad labor that takes place in the production in the region. Total bad labor of production would correspond to domestic plus exports, while footprints of consumption accounts for domestic plus imports. Regions are presented from highest to lowest GDP per PPP per capita. In OECD Europe and in North America, the contribution of imports and overseas production to bad labor footprints is up to 62%–78%, which is significantly more than the share of imports in the total labor footprint (41%–51%). This difference suggests that imports are relatively more bad-labor intensive, in persons in bad labor per persons in total labor, than domestic production in those regions. At the same time, in the developing regions of Latin America, Asia Pacific, and Africa, imports account for little or virtually no impact on their bad labor footprints (1%–11%), but exports can correspond to a significant amount of bad labor in those regions (up to 31%).

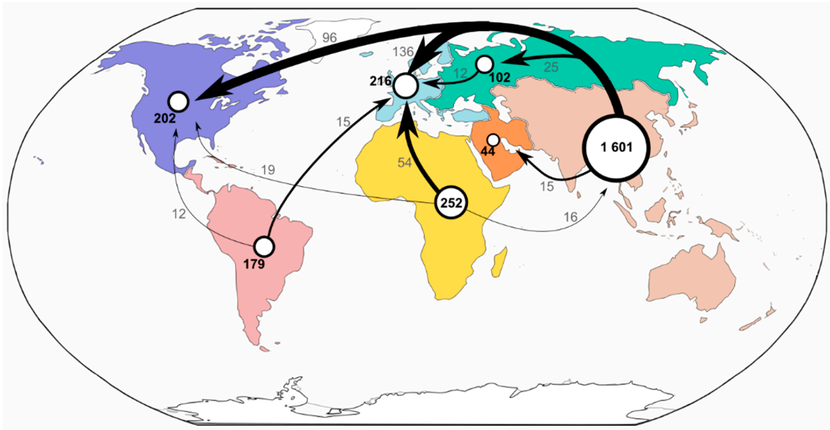
Approximately 16% of total labor was associated to the production of goods consumed in other regions. Similarly, bad labor conditions associated with global supply chains corresponded to 15%–20% of total bad labor happening globally (15% for low-skilled labor, 17% for forced labor, 18% for occupational health damage, 19% for child labor, 19% for vulnerable employment, and 20% for hazardous child labor). Women represented 38% of total labor associated to products traded between regions. We highlight that those share represent globalization of production and consumption between the seven regions used here, and not between individual countries.

Figure 1 illustrates the main flows of labor embodied in traded products within regions (circles) and between regions (arrows). All flows represented account for at least 2% of total labor/bad labor in inter-regional trade. In absolute values, flows of bad labor associated with foreign consumption follow the same path as total labor. Figure A1, in the Appendix, shows all major flows of bad labor associated with inter-regional trade. Imports to OECD Europe account for 46% of total labor and 50%–51% of all bad labor conditions associated with inter-regional trade. With a similar GDP and around 80% of the population of Europe OECD, North America accounts for 28% of total labor and 24%–29% of bad labor conditions associated to trade across regions.

Table 2. Labor and bad labor footprints of each region and footprints of trade.

		North America	Europe OECD	Non-OECD Europe	Middle East	Latin America	Asia and the Pacific	Africa
Total employment	**Footprint** (1000 p-y_{eq})	**340,597**	**442,142**	**140,138**	**64,629**	**193,651**	**1,643,781**	**261,241**
	Domestic share of footprint	*59%*	*49%*	*73%*	*68%*	*92%*	*97%*	*96%*
	Imports share of footprint	*41%*	*51%*	*27%*	*32%*	*8%*	*3%*	*4%*
	Exports footprint	10,732	23,263	22,692	15,243	36,583	283,298	99,223
	Exports share of production	*5%*	*10%*	*18%*	*26%*	*17%*	*15%*	*28%*
Vulnerable employment	**Footprint** (1000 p-y_{eq})	**77,436**	**135,302**	**27,759**	**24,443**	**64,262**	**539,060**	**149,147**
	Domestic share of footprint	*33%*	*28%*	*49%*	*66%*	*93%*	*97%*	*98%*
	Imports share of footprint	*67%*	*72%*	*51%*	*34%*	*7%*	*3%*	*2%*
	Exports footprint	1367	3821	3047	5955	16,010	99,916	66,816
	Exports share of production	*5%*	*9%*	*18%*	*27%*	*21%*	*16%*	*31%*
Low-skilled labor	**Footprint** (1,000 p-y_{eq})	**69,642**	**104,618**	**25,589**	**9858**	**36,885**	**768,777**	**75,923**
	Domestic share of footprint	*32%*	*22%*	*45%*	*48%*	*89%*	*99%*	*97%*
	Imports share of footprint	*68%*	*78%*	*55%*	*52%*	*11%*	*1%*	*3%*
	Exports footprint	1,136	2,166	2,450	1,493	4,058	118,907	32,602
	Exports share of production	*5%*	*9%*	*18%*	*24%*	*11%*	*14%*	*31%*
Occupational health	**Footprint** (1000 DALYs)	**2138**	**3616**	**1540**	**697**	**1590**	**15,444**	**3814**
	Domestic share of footprint	*36%*	*29%*	*76%*	*78%*	*91%*	*97%*	*98%*
	Imports share of footprint	*64%*	*71%*	*24%*	*22%*	*9%*	*3%*	*2%*
	Exports footprint	34	96	286	235	374	2,458	1,707
	Exports share of production	*4%*	*8%*	*20%*	*30%*	*21%*	*14%*	*31%*
Child labor	**Footprint** (1000 p-y_{eq})	**13,149**	**26,524**	**8,025**	**3,037**	**9,632**	**96,437**	**43,016**
	Domestic share of footprint	*28%*	*27%*	*66%*	*67%*	*91%*	*96%*	*99%*
	Imports share of footprint	*72%*	*73%*	*34%*	*33%*	*9%*	*4%*	*1%*
	Exports footprint	238	585	922	902	4,375	13,098	17,807
	Exports share of production	*6%*	*8%*	*15%*	*31%*	*33%*	*12%*	*29%*
Hazardous child labor	**Footprint** (1000 p-y_{eq})	**8276**	**16,807**	**5966**	**2270**	**6352**	**41,788**	**25,589**
	Domestic share of footprint	*38%*	*36%*	*75%*	*76%*	*92%*	*94%*	*99%*
	Imports share of footprint	*62%*	*64%*	*25%*	*24%*	*8%*	*6%*	*1%*
	Exports footprint	201	494	779	761	2,923	5,553	10,601
	Exports share of production	*6%*	*8%*	*15%*	*31%*	*33%*	*12%*	*29%*
Forced labor	**Footprint** (1000 p-y_{eq})	**901**	**1822**	**897**	**332**	**728**	**6822**	**1678**
	Domestic share of footprint	*34%*	*38%*	*81%*	*80%*	*92%*	*97%*	*98%*
	Imports share of footprint	*66%*	*62%*	*19%*	*20%*	*8%*	*3%*	*2%*
	Exports footprint	20	52	126	112	353	938	688
	Exports share of production	*6%*	*7%*	*15%*	*30%*	*34%*	*12%*	*29%*

Figure 1. Gross flows of labor embodied in traded goods, in million persons-year equivalent [1].



[1] The sizes of the circles indicate domestic trade and thickness of the arrows indicate the volume of labor embodied in the flows between regions.

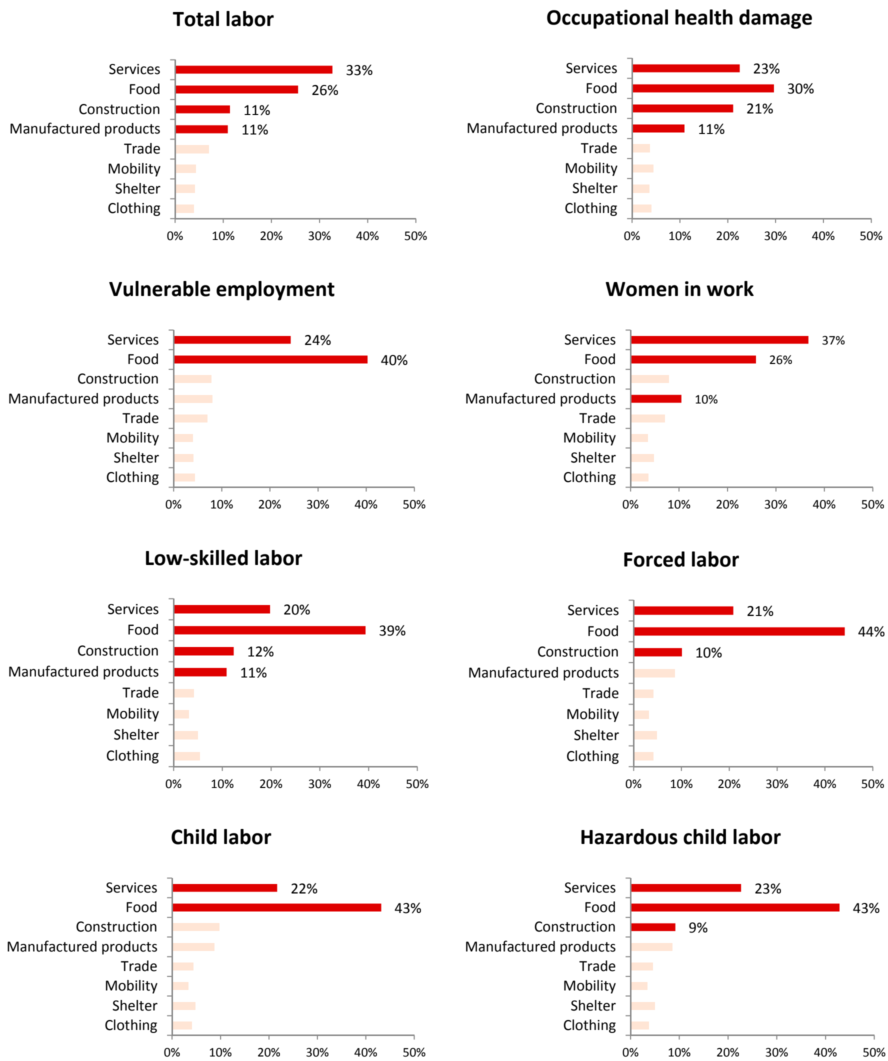
Most bad labor conditions are associated with intra-regional trade. Regarding inter-regional trade, the majority of bad labor associated with exchanges flows from the Asia Pacific and Africa regions to developed regions; flows from Asia Pacific to Europe OECD and North America correspond to almost half of all labor embodied in inter-regional trade. These trades are also responsible for over 60% of low-skilled labor, 41% of vulnerable employment, 39% of DALYs, 34% of forced labor, 29% of child labor, and only 22% of hazardous child labor. Flows from Africa to these same developed regions, however, account for only 11% of total labor embodied in inter-regional trade, but almost 20% of all DALYs and vulnerable employment and over one quarter of all child and hazardous child labor. These flows are significantly different from the flows of value added in inter-regional trade. For the latter, exports from Europe OECD and North America sum 45%, while exports from Asia and the Pacific correspond to 28%.

3.2. The Contribution of Consumption to Bad Labor Footprints

Figure 2 presents the contribution of each consumption category to the global bad labor footprints. It shows the *drivers* for the footprints, that is, all the impacts associated to the upstream supply chains of the consumption of products in each category. The consumption categories are organized according to their contribution to total labor footprint in the world. Bars in dark color represent categories that contribute to more than 10% of total labor and bad labor footprints.

Globally, the consumption of services is the main driver for employment, corresponding to around one third of workers worldwide, but is not responsible for most of the bad labor conditions. Food consumption drives 40% of all vulnerable labor in the world, and over half of all employment driven by food production are in a vulnerable situation. It also induces around 40% of low-skilled workers, and over 40% of child and forced labor. The construction drives one fifth of all DALYs, and it has the lowest proportion of female workers; only 26% of all workers in activities related to construction are women.

Figure 2. Contribution of each consumption category to total and to bad labor footprints in the world.



Industries related to each consumption category are displayed in Table S1.6 in the Appendix, and figures for the contribution of each consumption category to total and to bad labor footprints in each region are found in the results section of the Supplementary Material (S1).

Bad labor footprints are concentrated in different consumption categories, depending on the region. There are some similarities. Services drive the highest share of total labor footprint in all regions except for Asia Pacific and Africa. Occupational health damages result mainly by the consumption of services, food products, construction services, and manufactured products.

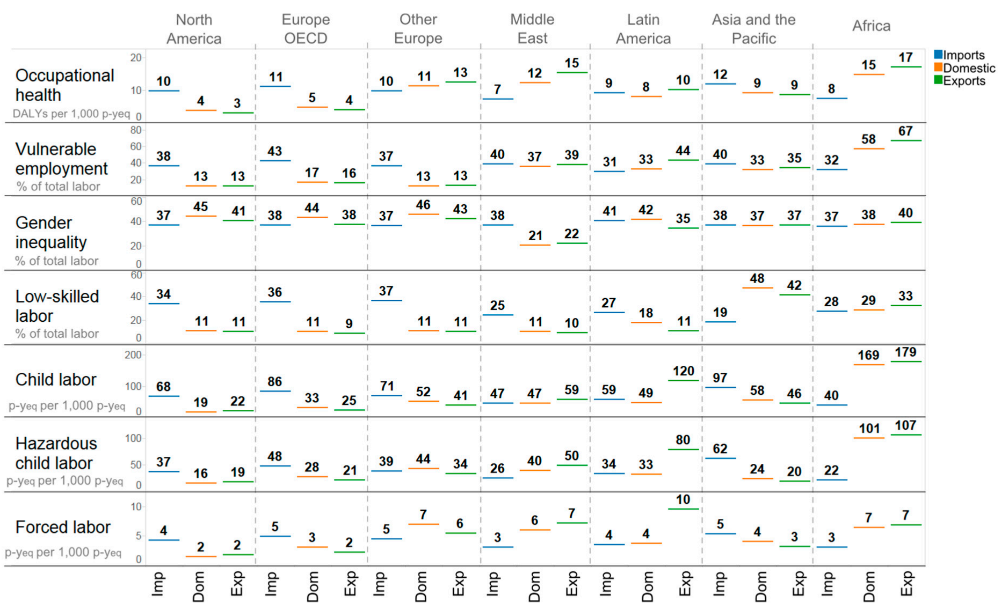
Food consumption represent higher share of the bad labor footprint in most of the regions. It is especially high for child and forced labor. In the developed economies of North America and OECD Europe, food products represent the second highest contribution to total labor (17% and 18%, respectively), but are largest source of bad labor conditions. Europe OECD not only has a higher bad labor footprint than North America, but also higher contribution from food products in general due to its higher imports from Asia and Africa, regions that have the majority of their bad labor conditions in food production. Absolute footprints for each sector are available in the Table S1.2.1 in the online Supplementary Material (S1), ranked in decreasing footprint.

A complete spreadsheet detailing the flows between the seven studied regions categorized by production sector is available in the online Supplementary Material (S2). Although the sectorial classification is the same as for the consumption categories, the spreadsheet shows where the production occurs, and not the consumption as a driver for the footprints.

3.3. Bad Labor Intensities

Figure 3 offers a breakdown of share of bad labor conditions per unit labor footprint. These are presented for imported products (left bar, in blue), goods produced and traded domestically (middle bar, in orange), and exported products (bar to the right, in green). The share of bad labor is usually highest for domestic production and exports in developing regions, while it is always highest for imports into Europe OECD and North America. It appears that products exported from Latin America to other regions have a significantly higher share of vulnerable employment and persons in child and forced labor than products produced and traded domestically. In contrast, African products have similar intensities for both domestically-traded and exported products.

Figure 3. Bad labor intensity of total labor footprint for imports (left; blue), intra-regional trade (middle; orange), and exports (right; green) [1].



[1] Units: DALYs per 1000 p-y_{eq} for occupational health damage; share of total employment for vulnerable employment, gender inequality, and low-skilled labor; and p-y_{eq} in child or forced work per 1000 p-y_{eq} for child labor, hazardous child labor, and forced labor.

One could measure bad labor intensity from an economic, lifestyle, or probability perspective. To cover different perspectives, four measures of intensities were calculated and compared and are presented in Table 3. The first two measures cover an economic perspective, using bad labor per GDP and bad labor per expenditure (GDE, gross domestic expenditure) as indicators. The former measures the bad labor footprint of each region per unit of production, that is, value added to the economy, and considers the economic output of the region as the main target of policies and analysis. The latter evaluates the bad labor footprint per million euros of consumption of final products by households, governments, and for capital formation. This approach considers final consumption to be the ultimate goal of production systems. The third measure is bad labor per capita. This measure considers bad labor footprints per total population of the consuming region, and considers how many people benefit from lifestyles supported by the labor and bad labor associated with their consumed products. The fourth measure is the share of bad labor in total labor footprints, and measures how bad a certain flow or footprint is; higher intensities indicate higher probability that the purchase of products from a certain consumption category has been produced under bad labor conditions.

Table 3. Labor and bad labor intensities of each region, based on different measures.

		North America	**Europe OECD**	**Non-OECD Europe**	**Middle East**	**Latin America**	**Asia Pacific**	**Africa**
Occupational health damage (DALYs)	per GDP (1)	0.2	0.3	1.0	0.8	0.9	1.7	5.6
	per GDE (2)	0.2	0.3	1.1	0.9	0.9	1.8	5.7
	per 1000 inhabitants	4.8	6.7	5.9	2.5	3.4	4.1	4.4
	per 1000 p-y_{eq}	6.3	8.2	11.0	10.8	8.2	9.4	14.6
Vulnerable employment (p-y_{eq})	per GDP (1)	7	11	19	27	37	60	220
	per GDE (2)	6	11	19	30	37	61	225
	per 1000 inhabitants	173	250	106	89	139	143	171
	per 1000 p-y_{eq}	227	306	198	378	332	328	571
Women in workforce (p-y_{eq})	per GDP (1)	12	15	42	19	47	68	148
	per GDE (2)	12	14	42	21	47	70	151
	per 1000 inhabitants	319	331	234	62	177	162	115
	per 1000 p-y_{eq}	419	406	438	265	423	371	383
Low-skilled workers (p-y_{eq})	per GDP (1)	6	8	17	11	21	85	112
	per GDE (2)	6	9	18	12	21	88	114
	per 1000 inhabitants	156	193	98	36	80	204	87
	per 1000 p-y_{eq}	205	237	183	153	191	468	291
Child labor (p-y_{eq})	per GDP (1)	1	2	5	3	6	11	64
	per GDE (2)	1	2	6	4	6	11	65
	per 1000 inhabitants	30	49	31	11	21	26	49
	per 1000 p-y_{eq}	39	60	57	47	50	59	165
Hazardous child labor (p-y_{eq})	per GDP (1)	1	1	4	3	4	5	38
	per GDE (2)	1	1	4	3	4	5	39
	per 1000 inhabitants	19	31	23	8	14	11	29
	per 1000 p-y_{eq}	24	38	43	35	33	25	98

Table 3. *Cont.*

		North America	Europe OECD	Non-OECD Europe	Middle East	Latin America	Asia Pacific	Africa
Forced labor ($p\text{-}y_{eq}$)	per GDP (1)	0.1	0.1	0.6	0.4	0.4	0.8	2.5
	per GDE (2)	0.1	0.1	0.6	0.4	0.4	0.8	2.5
	per 1000 inhabitants	2.0	3.4	3.4	1.2	1.6	1.8	1.9
	per 1000 $p\text{-}y_{eq}$	2.6	4.1	6.4	5.1	3.8	4.2	6.4
Total labor ($p\text{-}y_{eq}$)	per GDP (1)	29	36	95	71	111	183	386
	per GDE (2)	28	37	36	80	112	187	394
	per 1000 inhabitants	761	815	535	235	420	435	300
	per 1000 $p\text{-}y_{eq}$	-	-	-	-	-	-	-

(1) GDP = Gross Domestic Product, in million euros; (2) GDE = Gross Domestic Expenditure, in million euros.

Bad labor intensities measured based on economic production and consumption are particularly high for Africa, due to its high labor footprint and low GDP and GDE. OECD Europe and North America have among the highest footprints per capita. Both OECD Europe and North America present the highest total labor footprint per capita, with 815 and 761 $p\text{-}y_{eq}$ required to produce goods and services consumed for each 10,000 inhabitants in those regions, respectively. The Middle East was the only region identified with a bad labor footprint for gender inequality. This region employs only 62 women per 1000 inhabitants, or 265 women per 1000 $p\text{-}y_{eq}$ in total labor.

Africa also has the highest share of bad labor in total labor footprints, except for low-skilled labor, where Asia Pacific leads with almost half of its workers performing low-skill production activities. The shares of bad labor in total labor for each region and production sector are ranked from higher to lower in Table A1, in the Appendix.

Higher shares of bad labor in total labor footprints are found in food products, except for gender inequality and occupational health, where construction activities have the worst conditions.

4. Discussion

This section is divided into two parts. First, we discuss the main findings of the study, followed by a discussion of the identified limitations and uncertainties in the model and suggest ways to reduce these uncertainties in future work.

4.1. The Social Footprints of Trade

The fact that most bad labor conditions are in developing countries is intimately connected to both poor living and labor conditions in these regions and to the high population and low labor productivity. As previously shown for employment footprints [36,37], transfers of bad labor across regions also appear to be linked to affluence. However, while 15% of bad labor conditions are mainly driven by consumption in rich countries in North America and OECD Europe, around 85% take place in the production of goods traded within a region.

Different measures of bad labor intensities can provide divergent results. Bad labor intensities from the production perspective are significantly lower for developed regions in comparison to developing ones.

However, this difference can be significantly reduced (or even reversed) when the bad labor intensity is measured with reference to the consuming population.

By looking at the share of bad labor in the total labor footprints of traded goods, we confirm that developed countries have similar or better labor conditions in export-dominated industries than that of domestic-oriented ones, mainly due to the exports of high value-added products. Our results show that imports to those regions, however, are associated with nearly four times worse labor conditions per unit of labor than that of domestic production. In contrast, export-dominated industries in developing regions tend to present similar or worse labor conditions than those of domestic production. This appears to be related to the fact that developing regions are specialized in the exports of primary products and manufacturing stages that are intensive in low-skilled labor [37], where most bad labor conditions are concentrated. We can conclude that not only is the share of bad labor higher in developing economies than in developed ones, but also that a significant proportion of industries associated with bad labor conditions occurs in developing countries. Labor availability and labor costs play an important role in the globalization of supply chains, and developing regions are abundant in low-skilled labor [37]. Low-skilled labor is not considered a bad labor condition in itself, but a dominant share of low-skilled workers in trade flows are considered as sub-optimal working conditions in the economy as a whole. That calls for an articulation between local and regional development policies and global supply chain sustainability policies to guarantee fair working conditions throughout production processes worldwide.

Food production occupies around one third of global employment and suffers from worse labor conditions than other economic sectors. That is likely connected to the fact that agriculture and fishing are ultimately an activity of last resort. This sector not only includes those who farm, hunt and fish as an occupation, but also subsistence farmers, especially in areas with high incidence of poor rural households. That is true for not only developing economies, but also for developed countries. Subsistence agriculture and informal markets constitute a potential uncertainty to our study and is discussed in Section 4.2.

Simply reducing the consumption of goods produced in developing regions with a high incidence of bad labor conditions could lead to positive impacts on the developed economies' footprints. Nevertheless, it could lead to more negative impacts in poor households and reduce the positive impacts of employment and income generation in these developed regions. With over 80% of the bad labor impacts linked to intra-regional trade, local and regional policies for poverty alleviation will have a higher impact on bad labor mitigation than global supply chain policies.

4.2. Limitations and Further Research

Four main sources of uncertainty can be identified in the modeling performed here. Further research in these areas is recommended to increase robustness of results. The first two relate to (1) data availability and consequently to the uncertainties introduced through (2) disaggregation and allocation. These uncertainties are exceptionally higher for forced and child (and hazardous child) labor due to higher levels of uncertainties inherent in the source data and because the source data are more aggregated at both sectorial and regional levels. Uncertainties in the quantification of child and forced labor in different regions due to the illegal and hidden nature of these workers are well discussed in the reports consulted [18,51]. Due to the imprecision of these estimates and their association with human trafficking between countries and regions, they are aggregated into large regions and broad economic sectors. The disaggregation and allocation of this data to the MRIO regions and sectors were made under considerable assumptions, based on low-skilled labor in each sector, and might increase the correlation between labor embodied in trade and bad labor embodied in trade. The results were re-aggregated in broad regions and consumption categories to avoid giving the misleading illusion of precision.

We present the trade-related impacts for the seven global regions, while there are clearly additional trade-related impacts within each of the world regions (for example, between Mexico and the United States, considered intra-regional in the current study). Accounting for trade at the national level will significantly increase the proportion of labor and bad labor footprints associated with internationally traded products. We modeled total labor, vulnerable employment, and low-skilled labor in international trade at the level of detail of the MRIO (43 countries + 5 "rest of the world" regions). In this new assessment, 22% of total labor, 25% of total vulnerable employment, and 19% of total low-skilled labor were associated to internationally traded products and services, against 16%, 19% and 15% found in the inter-regional trade. The aggregation of labor-abundant developing countries in the "rest of the world" regions, however, also present an incomplete picture of labor associated with products traded between the countries in those regions.

The two latter sources of uncertainties are those inherent to the input-output framework. MRIO uses "product groups" to ensure tractability of all goods and services in the economy. This has the effect that labor impacts are associated to the average of the product group, while different types of products within the same product group generally embody different impacts, and are sold to different consumers. This represents an inherent imprecision to the model, for which the contribution has not yet been quantified in terms of the effects on impacts embodied in trade [64–68]. Furthermore, labor (and land, capital, energy, and other factors of production) can differ significantly both: (a) regionally within a single country; and (b) between small and medium domestically-oriented and large-scale exported-oriented production inside a same sector. Exemplifying the case of agriculture production in Brazil (data for 2006), small and medium family-owned properties correspond to almost 85% of all farms, three thirds of total employment in agriculture, but only 38% of agricultural GDP and one quarter of all land occupied for agriculture. Those small and medium properties accounted for only 19% of all agricultural exports in the same year [69]. This example reveals that exported agricultural products from Brazil are more capital intensive and less labor-intensive than agriculture destined for domestic consumption.

This observation can also be linked to the fourth identified uncertainty, which is the inability to separate formal and informal economy in the current MRIO model. While small and medium familiar agricultural properties concentrate most of the labor force in the agricultural sector, not all of their production will necessarily be traded in the formal market. In Eastern African countries, for example, smallholder farming accounts for around 75% of total agriculture production and over 75% of total employment in agriculture, the majority of these being subsistence farmers [70]. In South Africa, around 5 million workers are estimated to be involved in subsistence activities [71]. Subsistence farming is generally outside of the formal economy, and thus out of the MRIO boundaries. Generally, neither economic nor physical production/consumption of subsistence farming is included in the input-output system. However, persons for whom subsistence farming is the main work activity are included in labor force surveys as persons employed in agriculture. Global poverty dramatically affects agricultural households, and three out of every four poor people live in agriculture-dependent households [72]. The lack of information on the share of subsistence farmers in total employment results in a great challenge to separate these from the formal economy in the IO system. Just like in subsistence farming, a large part of children involved in production are unpaid family workers that could be involved in informal subsistence activities and in housework activities that do not contribute economically to the household [73,74]. Since labor statistics cover both the formal and the informal economy, total labor and bad labor associated with commercial trade are potentially overestimated.

5. Conclusions

In this study, we provide a new perspective on how to account for social impacts of globalization. While most of the existing assessments only consider activities directly related to the production of goods, MRIO analysis quantifies the full supply chain of goods and services. These include all steps from material and energy extraction, manufacture of intermediate products, and the direct production of the final goods.

Globalization raises the question of to what extent the bad labor conditions worldwide are linked to different products consumed overseas. We confirm that the transfer of bad labor occurs mainly from developing to developed countries. Imports correspond to 62% to 78% of rich regions' bad labor footprints. Imports to regions with low GDP per capita do not contribute to their bad labor footprints. Up to 30% of the bad labor conditions in these countries, however, are related to the production of exported products.

While the production of services provides the largest share of employment globally, the largest share of bad labor in the world occurs in food production. Whilst the largest flows of bad labor occur within and from the Asia and the Pacific region, the most intensive impact of bad labor per unit value of the traded product generally occurs in Africa, mainly in food production. In all regions, construction activities present a higher density for gender inequality and occupational health, shown by a lower share of women and a higher volume of DALYs per 1000 workers, respectively. The bad labor intensities of imports, exports, and domestic trade also present a distinct profile in each region. The export-oriented production in affluent economies present better labor conditions than those for domestic consumption, and significantly better conditions than those from imported products. In less developed regions, in contrast, both domestic and export-oriented productions are more bad labor intensive.

In this article, we showed that (i) as expected, there is a net flow of bad labor conditions embodied in products traded from developing to developed regions; (ii) bad labor footprints caused by wealthy lifestyles of rich regions are primarily, but not solely, due to the import of goods from lower income regions; and (iii) whilst the largest quantities of "bad labor" occur in rapidly developing regions, the intensity of bad labor intensities embodied in goods is still often highest in the poorest regions. In terms of type of traded goods, the group of food products stands out in both volume and intensity of embodied bad labor. As our society develops further, the reduction in inequalities and labor related impacts are going to be integral in achieving social sustainability. Clearly, there is a global responsibility across both producers and consumers in realizing this goal.

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Author Contributions

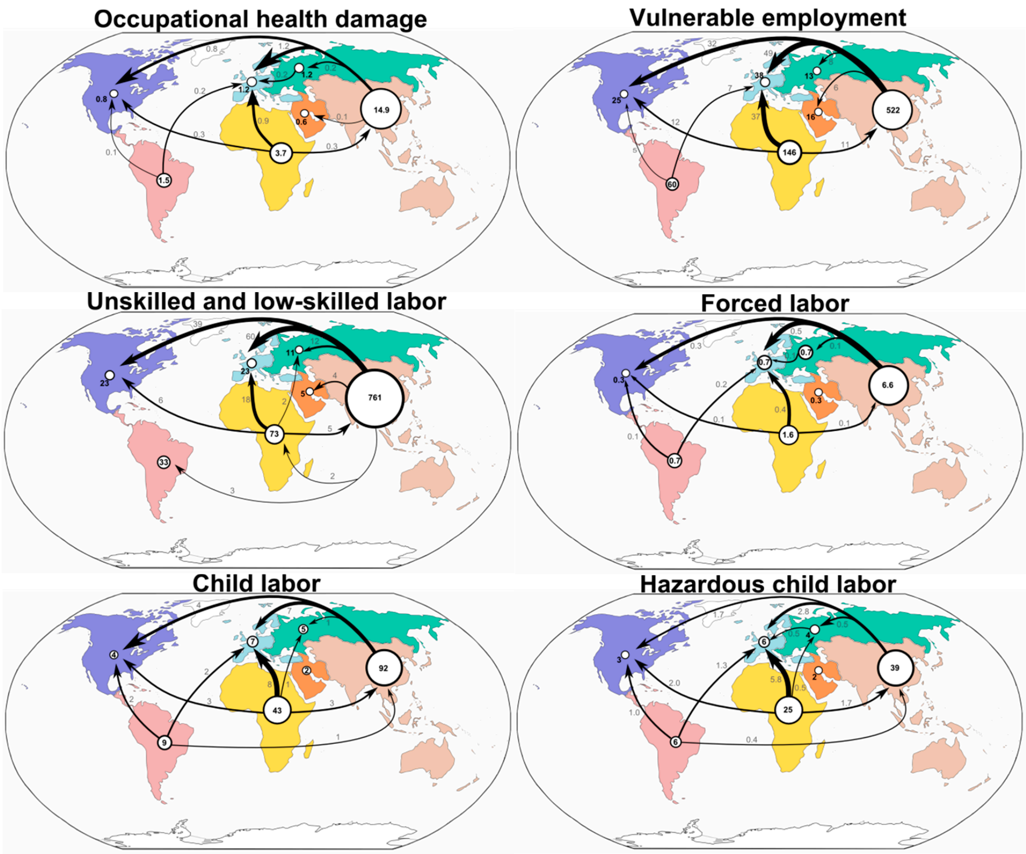
Richard Wood, Edgar Hertwich and Mark Huijbregts conceived and designed the study. Richard Wood and Moana Simas structured the project. Moana Simas and Laura Golsteijn collected and processed the data and wrote the article. Richard Wood supervised the research. All authors contributed to preparing and approving the manuscript.

Supplementary Materials

Supplementary materials can be accessed at: http://www.mdpi.com/2071-1050/6/11/7514/s1.

Appendix

Figure A1. Gross flows of bad labor embodied in traded goods [1].



[1] Size of the circles indicates domestic trade (big circles mean high volume) and thickness of the arrows indicate the volume of bad labor embodied in the flows between regions. Flows are identified for the following indicators: Occupational health damage (in million DALYs), vulnerable employment, unskilled and low-skilled labor, forced labor, child labor, and hazardous child labor (all in million p-y_{eq}). Data used for elaboration of this map is found in Table S1.2.2 in the Supplementary Material.

Table A1. Bad labor intensity of total labor footprints for each sector and region [1].

	Vulnerable employment (*)			**Low-skilled labor (*)**			**Gender inequality (*)**			**Occupational health (**)**			**Child labor (*)**			**Hazardous child labor (*)**			**Forced labor (*)**		
	Reg	**Cat**	**V**	**Reg**	**Cat**	**V**	**Reg**	**Cat**	**V**	**Reg**	**Cat**	**V**	**Reg**	**Cat**	**V**	**Reg**	**Cat**	**V**	**Reg**	**Cat**	**V**
1	Af	Food	**819**	AP	Food	**691**	NA	Cons	**123**	AP	Cons	**30**	Af	Food	**192**	ME	Food	**133**	OE	Food	**17**
2	ME	Food	**752**	AP	Cons	**581**	EU	Cons	**129**	OE	Cons	**26**	OE	Food	**178**	OE	Food	**132**	ME	Food	**16**
3	LA	Food	**636**	AP	Cloth	**539**	AP	Cons	**135**	Af	Cons	**20**	LA	Food	**173**	Af	Food	**114**	LA	Food	**14**
4	EU	Food	**625**	AP	Man	**504**	Af	Cons	**196**	Af	Cons	**20**	ME	Food	**172**	LA	Food	**114**	OE	Shelt	**11**
5	NA	Food	**580**	LA	Shelt	**491**	ME	Serv	**218**	EU	Cons	**20**	EU	Food	**146**	EU	Food	**93**	EU	Food	**10**
6	OE	Food	**531**	AP	Shelt	**482**	LA	Cons	**218**	Af	Food	**18**	Af	Shelt	**144**	Af	Shelt	**85**	NA	Food	**8.2**
7	AP	Food	**459**	OE	Cloth	**403**	OE	Cons	**245**	NA	Cons	**18**	Af	Trade	**141**	Af	Trade	**84**	Af	Food	**7.5**
8	AP	Trade	**395**	EU	Food	**400**	ME	Man	**249**	LA	Cons	**17**	Af	Serv	**139**	Af	Serv	**83**	AP	Food	**6.5**
9	Af	Cloth	**376**	NA	Cloth	**397**	ME	Mob	**250**	ME	Food	**16**	Af	Mob	**134**	Af	Mob	**80**	LA	Shelt	**5.9**
10	Af	Shelt	**371**	Af	Food	**395**	AP	Mob	**259**	Af	Mob	**16**	Af	Cloth	**134**	Af	Cloth	**79**	Af	Shelt	**5.7**
11	ME	Trade	**362**	NA	Food	**365**	NA	Mob	**267**	Af	Shelt	**14**	Af	Man	**132**	Af	Man	**79**	Af	Trade	**5.5**
12	AP	Cloth	**354**	NA	Shelt	**364**	EU	Mob	**270**	Af	Man	**14**	Af	Cons	**118**	OE	Shelt	**76**	Af	Cloth	**5.4**
13	LA	Cons	**348**	EU	Cloth	**363**	ME	Trade	**284**	ME	Mob	**13**	NA	Food	**114**	Af	Cons	**70**	Af	Serv	**5.4**
14	LA	Trade	**347**	OE	Food	**327**	ME	Cloth	**293**	OE	Shelt	**13**	OE	Shelt	**95**	NA	Food	**69**	Af	Mob	**5.3**
15	AP	Shelt	**337**	EU	Shelt	**322**	EU	Cloth	**308**	OE	Mob	**13**	AP	Food	**93**	LA	Shelt	**54**	Af	Man	**5.2**
16	Af	Trade	**337**	NA	Man	**314**	AP	Cloth	**313**	ME	Man	**13**	EU	Shelt	**82**	EU	Shelt	**52**	EU	Shelt	**5.1**
17	Af	Mob	**328**	AP	Mob	**296**	LA	Food	**313**	EU	Shelt	**13**	LA	Shelt	**82**	NA	Shelt	**44**	AP	Cons	**5.0**
18	Af	Serv	**318**	ME	Cloth	**293**	Af	Mob	**319**	OE	Food	**13**	NA	Shelt	**71**	AP	Food	**40**	NA	Shelt	**4.9**
19	ME	Shelt	**317**	Af	Cloth	**269**	OE	Mob	**334**	OE	Man	**13**	AP	Cons	**69**	AP	Cons	**29**	Af	Cons	**4.6**
20	LA	Mob	**300**	EU	Man	**261**	NA	Food	**341**	Af	Cloth	**12**	AP	Shelt	**63**	AP	Shelt	**28**	AP	Shelt	**4.4**
21	EU	Cloth	**297**	NA	Cons	**252**	EU	Man	**343**	EU	Food	**12**	ME	Shelt	**41**	ME	Shelt	**26**	ME	Shelt	**3.7**
22	ME	Mob	**291**	AP	Trade	**234**	Af	Serv	**345**	LA	Food	**12**	AP	Mob	**37**	NA	Cons	**23**	ME	Cloth	**3.0**
23	ME	Serv	**290**	Af	Shelt	**232**	Af	Trade	**350**	NA	Food	**11**	AP	Cloth	**34**	LA	Man	**19**	OE	Cons	**3.0**
24	EU	Shelt	**283**	ME	Food	**221**	NA	Cloth	**350**	LA	Mob	**11**	EU	Cloth	**33**	ME	Cloth	**18**	OE	Serv	**2.9**
25	AP	Mob	**279**	LA	Mob	**206**	ME	Shelt	**350**	NA	Shelt	**11**	AP	Man	**31**	EU	Cloth	**17**	AP	Mob	**2.6**
26	LA	Serv	**263**	LA	Trade	**195**	ME	Food	**355**	AP	Shelt	**11**	AP	Trade	**31**	LA	Cloth	**16**	ME	Serv	**2.6**

Table A1. *Cont.*

	Vulnerable employment (*)			**Low-skilled labor (*)**			**Gender inequality (*)**			**Occupational health (**)**			**Child labor (*)**			**Hazardous child labor (*)**			**Forced labor (*)**		
	Reg	**Cat**	**V**	**Reg**	**Cat**	**V**	**Reg**	**Cat**	**V**	**Reg**	**Cat**	**V**	**Reg**	**Cat**	**V**	**Reg**	**Cat**	**V**	**Reg**	**Cat**	**V**
27	ME	Cloth	**260**	Af	Trade	**195**	LA	Mob	**356**	AP	Man	**10**	NA	Cons	**30**	LA	Mob	**16**	OE	Trade	**2.6**
28	Af	Cons	**259**	LA	Serv	**194**	NA	Man	**357**	ME	Cloth	**10**	NA	Cloth	**30**	AP	Mob	**16**	OE	Mob	**2.6**
29	EU	Trade	**258**	Af	Mob	**190**	LA	Man	**363**	ME	Shelt	**10**	ME	Cloth	**30**	NA	Cloth	**16**	AP	Cloth	**2.5**
30	NA	Cloth	**248**	AP	Serv	**184**	OE	Man	**364**	AP	Food	**9.9**	LA	Man	**29**	NA	Man	**16**	ME	Trade	**2.5**
31	LA	Cloth	**245**	OE	Shelt	**184**	LA	Cloth	**365**	AP	Mob	**9.8**	OE	Cloth	**29**	OE	Cloth	**15**	ME	Man	**2.5**
32	NA	Shelt	**241**	ME	Shelt	**183**	AP	Trade	**370**	OE	Cloth	**9.7**	NA	Man	**27**	LA	Serv	**15**	OE	Cloth	**2.4**
33	Af	Cons	**235**	Af	Serv	**181**	Af	Cons	**372**	LA	Shelt	**9.2**	EU	Man	**26**	EU	Man	**15**	NA	Cloth	**2.4**
34	Af	Man	**224**	LA	Cons	**166**	EU	Food	**377**	LA	Man	**9.1**	EU	Mob	**26**	LA	Trade	**15**	ME	Mob	**2.3**
35	LA	Man	**218**	ME	Trade	**164**	AP	Man	**381**	AP	Cloth	**9.1**	LA	Cloth	**25**	EU	Mob	**15**	AP	Man	**2.3**
36	NA	Trade	**212**	EU	Mob	**160**	AP	Shelt	**381**	Af	Serv	**9.0**	LA	Mob	**24**	AP	Cloth	**14**	EU	Cloth	**2.3**
37	EU	Cons	**209**	OE	Man	**154**	OE	Food	**382**	EU	Mob	**8.8**	AP	Serv	**23**	EU	Cons	**14**	AP	Trade	**2.2**
38	AP	Serv	**203**	ME	Man	**152**	Af	Cloth	**388**	EU	Man	**8.5**	NA	Mob	**23**	ME	Trade	**14**	OE	Man	**2.0**
39	NA	Cons	**198**	NA	Mob	**152**	Af	Man	**389**	ME	Serv	**8.2**	ME	Trade	**23**	AP	Man	**14**	Af	Cons	**2.0**
40	EU	Mob	**193**	Af	Man	**150**	AP	Food	**400**	EU	Cloth	**8.2**	LA	Serv	**22**	LA	Cons	**14**	NA	Man	**1.9**
41	ME	Man	**189**	Af	Cons	**145**	OE	Shelt	**400**	NA	Man	**8.0**	LA	Trade	**22**	AP	Trade	**13**	NA	Cons	**1.9**
42	LA	Shelt	**180**	NA	Trade	**144**	OE	Cloth	**402**	NA	Cloth	**7.9**	EU	Trade	**21**	NA	Trade	**13**	LA	Man	**1.8**
43	OE	Trade	**180**	EU	Cons	**139**	Af	Food	**409**	NA	Mob	**7.8**	EU	Cons	**21**	NA	Mob	**13**	LA	Mob	**1.7**
44	OE	Shelt	**177**	ME	Mob	**136**	AP	Serv	**417**	LA	Cloth	**7.3**	LA	Cons	**20**	OE	Man	**13**	EU	Mob	**1.7**
45	NA	Mob	**168**	OE	Cons	**125**	EU	Shelt	**428**	Af	Trade	**6.4**	NA	Trade	**19**	EU	Trade	**13**	LA	Trade	**1.7**
46	EU	Serv	**143**	ME	Serv	**123**	EU	Trade	**432**	OE	Serv	**6.1**	ME	Man	**18**	OE	Cons	**12**	AP	Serv	**1.7**
47	AP	Cons	**131**	EU	Serv	**122**	LA	Trade	**432**	LA	Serv	**5.9**	OE	Man	**17**	ME	Man	**12**	EU	Man	**1.6**
48	NA	Serv	**113**	OE	Mob	**121**	NA	Shelt	**433**	ME	Trade	**4.9**	ME	Mob	**17**	EU	Serv	**11**	LA	Cloth	**1.6**
49	OE	Mob	**113**	LA	Man	**119**	Af	Shelt	**438**	AP	Serv	**4.5**	EU	Serv	**16**	ME	Mob	**11**	LA	Serv	**1.6**
50	OE	Cloth	**102**	OE	Trade	**118**	NA	Trade	**439**	OE	Trade	**4.3**	OE	Trade	**16**	ME	Serv	**11**	EU	Cons	**1.5**
51	AP	Man	**98**	EU	Trade	**117**	LA	Serv	**487**	LA	Trade	**4.2**	OE	Mob	**15**	OE	Trade	**11**	NA	Mob	**1.4**

Table A1. *Cont.*

	Vulnerable employment (*)			**Low-skilled labor (*)**			**Gender inequality (*)**			**Occupational health (**)**			**Child labor (*)**			**Hazardous child labor (*)**			**Forced labor (*)**		
	Reg	**Cat**	**V**	**Reg**	**Cat**	**V**	**Reg**	**Cat**	**V**	**Reg**	**Cat**	**V**	**Reg**	**Cat**	**V**	**Reg**	**Cat**	**V**	**Reg**	**Cat**	**V**
52	OE	Cons	**89**	OE	Serv	**115**	EU	Serv	**523**	AP	Trade	**3.4**	OE	Cons	**15**	OE	Serv	**11**	LA	Cons	**1.4**
53	NA	Man	**88**	LA	Cloth	**100**	NA	Serv	**527**	EU	Serv	**3.2**	ME	Serv	**14**	OE	Mob	**11**	EU	Trade	**1.4**
54	EU	Man	**86**	NA	Serv	**93**	OE	Trade	**532**	EU	Trade	**2.8**	OE	Serv	**14**	AP	Serv	**10**	NA	Trade	**1.2**
55	OE	Serv	**75**	Af	Cons	**85**	OE	Serv	**578**	NA	Serv	**2.7**	NA	Serv	**13**	NA	Serv	**9**	EU	Serv	**1.1**
56	OE	Man	**69**	LA	Food	**84**	LA	Shelt	**644**	NA	Trade	**2.3**	Af	Cons	**11**	Af	Cons	**9**	NA	Serv	**0.8**

[1] Values (V) in the following units: (*) = p-y_{eq} in bad labor per 1000 p-y_{eq} in total employment; (**) = DALYs per 1000 p-y_{eq} in total employment. Regions (Reg): Af = Africa; AP = Asia and the Pacific; EU = Europe OECD; LA = Latin America and the Caribbean; ME = Middle East; NA = North America; OE = Other Europe. Categories (Cat): Cloth = Clothing; Cons = Construction; Man = Manufactured products; Mob = Mobility; Serv = Services; Shelt = Shelter.

Conflicts of Interest

The authors declare no conflict of interest.

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